# A Bitmapper's Companion

epilys

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an introduction to basic bitmap mathematics and algorithms with code samples in **Rust**

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All non-screenshot figures were generated by hand in Inkscape unless otherwise stated.

The skull in the cover is a transformed bitmap of the skull in the 1533 oil painting by Hans Holbein the Younger, *The Ambassadors*, which features a floating distorted skull rendered in anamorphic perspective.

*A Bitmapper's Companion*, 2021
**Special Topics ▶ Computer Graphics ▶ Programming**
006.6'6–dc20

# Contents



intro

# Part I

# Introduction

intro

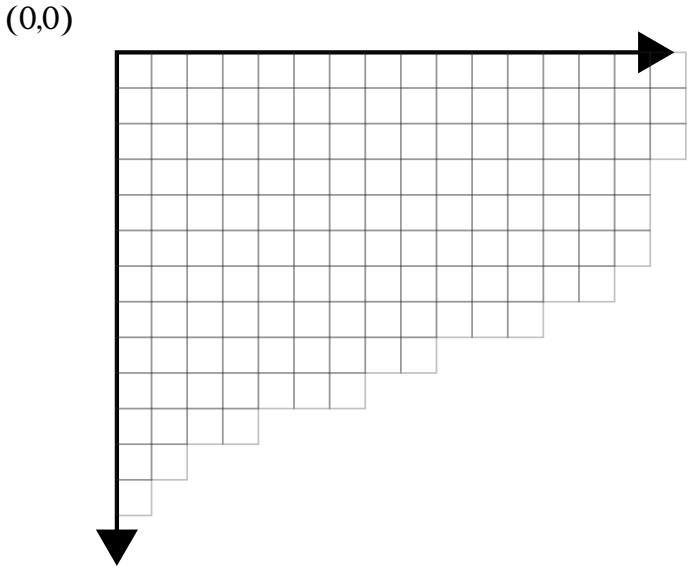
# Chapter 1



# Data representation

The data structures we're going to use is *Point* and *Image*. *Image* represents a bitmap, although we will use full RGB colors for our points therefore the size of a pixel in memory will be u8 instead of 1 bit.

We will work on the cartesian grid representing the framebuffer that will show us the pixels. The *origin* of this grid (i.e. the center) is at $(0, 0)$.




We will represent points as pairs of signed integers. When actually drawing them though, negative values and values outside the window's geometry will be

src/lib.rs: ignored (clipped).

This code file is a PDF attachment

intro

```rust
pub type Point = (i64, i64);

pub const fn from_u8_rgb(r: u8, g: u8, b: u8) -> u32 {
    let (r, g, b) = (r as u32, g as u32, b as u32);
    (r << 16) | (g << 8) | b
}
pub const AZURE_BLUE: u32 = from_u8_rgb(0, 127, 255);
pub const RED: u32 = from_u8_rgb(157, 37, 10);
pub const WHITE: u32 = from_u8_rgb(255, 255, 255);
pub const BLACK: u32 = 0;

pub struct Image {
    pub bytes: Vec<u32>,
    pub width: usize,
    pub height: usize,
    pub x_offset: usize,
    pub y_offset: usize,
}

impl Image {
    pub fn new(width: usize, height: usize, x_offset: usize, y_offset: usize) -> Self;
    pub fn draw(&self, buffer: &mut Vec<u32>, fg: u32, bg: Option<u32>, window_width:
↪   usize);
    pub fn draw_outline(&mut self);
    pub fn clear(&mut self);
    pub fn plot(&mut self, x: i64, y: i64);
    pub fn get(&mut self, x: i64, y: i64) -> u32;
    pub fn plot_ellipse(
        &mut self,
        (xm, ym): (i64, i64),
        (a, b): (i64, i64),
        quadrants: [bool; 4],
        _wd: f64,
    );
    pub fn plot_line_width(&mut self, point_a: Point, point_b: Point, wd: f64);
    pub fn flood_fill(&mut self, mut x: i64, y: i64);
}
```

# Chapter 2



# Displaying pixels to your screen

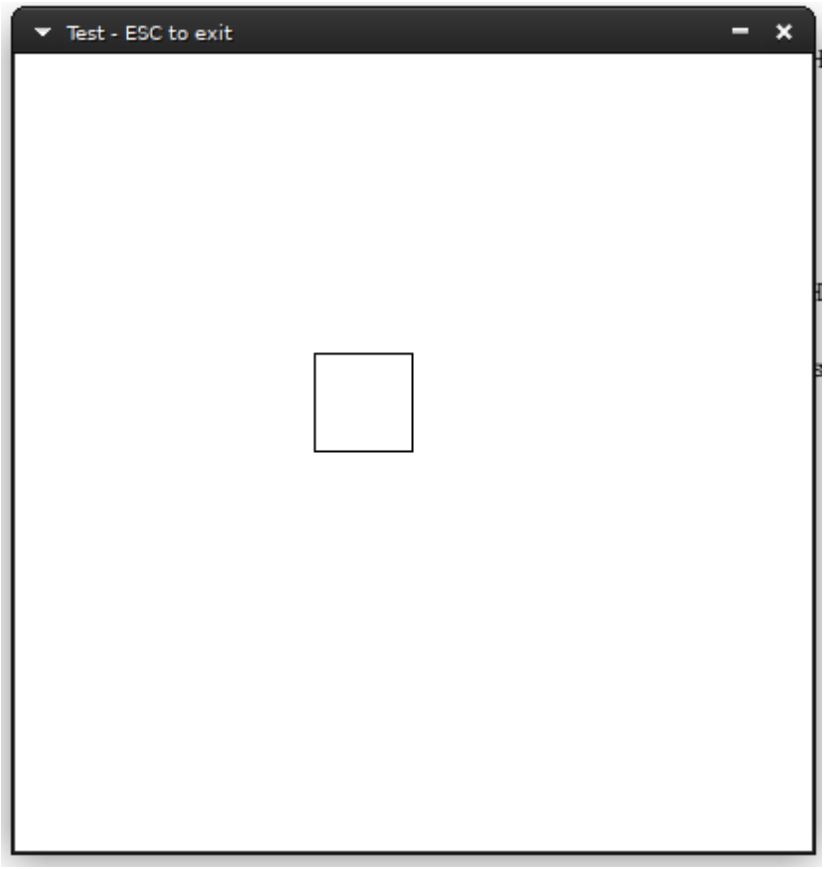
A way to display an *Image* is to use the `minifb` crate which allows you to create a window and draw pixels directly on it. Here's how you could set it up:

src/bin/introduction.rs:

This code file is a PDF attachment

```
use bitmappers_companion::*;
use minifb::{Key, Window, WindowOptions};

const WINDOW_WIDTH: usize = 400;
const WINDOW_HEIGHT: usize = 400;

fn main() {
    let mut buffer: Vec<u32> = vec![WHITE; WINDOW_WIDTH * WINDOW_HEIGHT];
    let mut window = Window::new(
        "Test - ESC to exit",
        WINDOW_WIDTH,
        WINDOW_HEIGHT,
        WindowOptions {
            title: true,
            //borderless: true,
            //resize: false,
            //transparency: true,
            ..WindowOptions::default()
        },
    )
    .unwrap();

    // Limit to max ~60 fps update rate
    window.limit_update_rate(Some(std::time::Duration::from_micros(16600)));

    let mut image = Image::new(50, 50, 150, 150);
    image.draw_outline();
    image.draw(&mut buffer, BLACK, None, WINDOW_WIDTH);

    while window.is_open()
         && !window.is_key_down(Key::Escape)
         && !window.is_key_down(Key::Q) {
        window
            .update_with_buffer(&buffer, WINDOW_WIDTH, WINDOW_HEIGHT)
            .unwrap();
        let millis = std::time::Duration::from_millis(100);
        std::thread::sleep(millis);
    }
}
```

Running this will show you something like this:


Test - ESC to exit

# Chapter 3

# Bits to byte pixels

Let's define a way to convert bit information to a byte vector:

```
pub fn bits_to_bytes(bits: &[u8], width: usize) -> Vec<u32> {
    let mut ret = Vec::with_capacity(bits.len() * 8);
    let mut current_row_count = 0;
    for byte in bits {
        for n in 0..8 {
            if byte.rotate_right(n) & 0x01 > 0 {
                ret.push(BLACK);
            } else {
                ret.push(WHITE);
            }
            current_row_count += 1;
            if current_row_count == width {
                current_row_count = 0;
                break;
            }
        }
    }
    ret
}
```

intro

# Chapter 4

# Loading `xbm` files in Rust

*The end of this chapter includes a short* **Rust** *program to automatically convert* `xbm` *files to equivalent* **Rust** *code.*

`xbm` files are C source code files that contain the pixel information for an image as macro definitions for the dimensions and a static `char` array for the pixels, with each bit column representing a pixel. If the width dimension doesn't have 8 as a factor, the remaining bit columns are left blank/ignored.

They used to be a popular way to share user avatars in the old internet and are also good material for us to work with, since they are small and numerous. The following is such an image:


Then, we can convert the `xbm` file from C to **Rust** with the following transformations:

```
#define news_width 48
#define news_height 48
static char news_bits[] = {
```

to

```
const NEWS_WIDTH: usize = 48;
const NEWS_HEIGHT: usize = 48;
const NEWS_BITS: &[u8] = &[
```

And replace the closing `}` with `];`.

We can then include the new file in our source code:

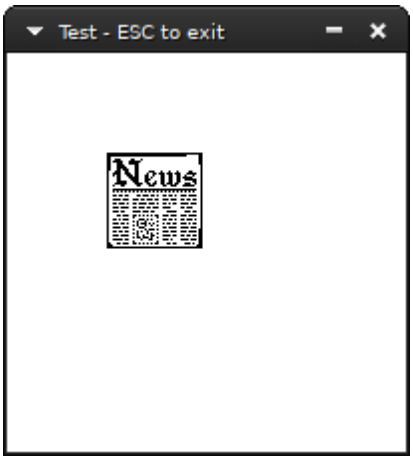
```
include!("news.xbm.rs");
```

load the image:

```
let mut image = Image::new(NEWS_WIDTH, NEWS_HEIGHT, 25, 25);
image.bytes = bits_to_bytes(NEWS_BITS, NEWS_WIDTH);
```



and finally run it:




The following short program uses the `regex` crate to match on these simple rules and print the equivalent code in `stdout`. You can use it like so:

```
cargo run --bin xbmtors -- file.xbm > file.xbm.rs
```

src/bin/xbmtors.rs:

This code file is a PDF attachment

```
use regex;
use regex::Regex;
use std::fs::File;
use std::io::prelude::*;

fn main() {
    let args = std::env::args().skip(1).collect::<Vec<String>>();
    if args.len() != 1 {
        println!("one argument expected, the xbm file path to convert.");
        return;
    }
    let mut file = match File::open(&args[0]) {
        Err(err) => panic!("couldn't open {}: {}", args[0], err),
        Ok(file) => file,
    };

    let mut s = String::new();
    if let Err(err) = file.read_to_string(&mut s) {
        panic!("couldn't read {}: {}", args[0], err);
    }

    let re = Regex::new(
        r"(?imx)
  ^\s*\x23\s*define\s+(?P<i>.+?)_width\s+(?P<w>\d\d*)$
```

```
    \s*
    ^\s*\x23\s*define\s+.+?_height\s+(?P<h>\d\d*)$
    \s*
    ^\s*static(\s+unsigned){0,1}\s+char\s+.+?_bits..\s*=\s*\{(?P<b>[^}]+)\};
",
    )
    .unwrap();

    let caps = re
        .captures(&s)
        .expect("Could not convert file, regex doesn't match :(");
    let ident = caps.name("i").unwrap().as_str().to_uppercase();
    let out = re.replace_all(&s, format!("const {i}_WIDTH: usize = $w;\nconst {i}_HEIGHT:
↪   usize = $h;\nconst {i}_BITS: &[u8] = &[$b];", i = &ident));
    println!("{}", out.trim());
}
```

lines

# Part II

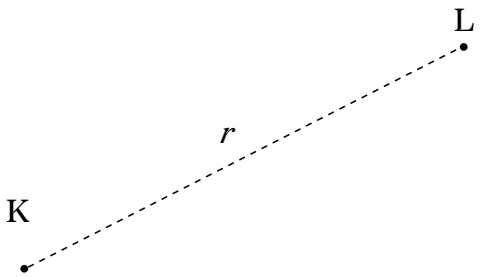
# Points And Lines

lines

# Chapter 5

# Distance between two points






Given two points, $K$ and $L$, an elementary application of Pythagoras' Theorem gives the distance between them as

$$r = \sqrt{(x_L - x_K)^2 + (y_L - y_K)^2} \tag{5.1}$$

which is simply coded:

```
pub fn distance_between_two_points(p_k: Point, p_l: Point) -> f64 {
    let (x_k, y_k) = p_k;
    let (x_l, y_l) = p_l;
    let xlk = x_l - x_k;
    let ylk = y_l - y_k;
    f64::sqrt((xlk*xlk + ylk*ylk) as f64)
}
```

lines

# Chapter 6

# Equations of a line



There are several ways to describe a line mathematically. We'll list the convenient ones for drawing pixels.

The equation that describes every possible line on a two dimensional grid is the *implicit* form $ax+by=c, (a,b) \neq (0,0)$. We can generate equivalent equations by adding the equation to itself, i.e. $ax + by = c \equiv 2ax + 2by = 2c \equiv a'x + b'y = c', a' = 2a, b' = 2b, c' = 2c$ as many times as we want. To "minimize" the constants $a, b, c$ we want to satisfy the relationship $a^2 + b^2 = 1$, and thus can convert the equivalent equations into one representative equation by multiplying the two sides with $\frac{1}{\sqrt{a^2+b^2}}$; this is called the normalized equation.

The *slope intercept form* describes any line that intercepts the $y$ axis at $b \in \mathbb{R}$ with a specific slope $a$:

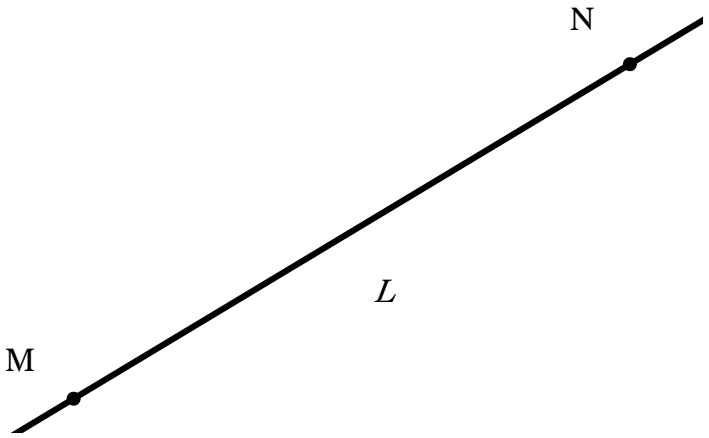
$$y = ax + b$$

The *parametric* form...

## 6.1 Line through a point $P = (x_p, y_p)$ and a slope $m$

$$y - y_p = m(x - x_p)$$

## 6.2 Line through two points




It seems sufficient, given the coordinates of two points $M, N$, to calculate $a, b$ and $c$ to form a line equation:

$$ax + by + c = 0$$

If the two points are not the same, they necessarily form such a line. To get there, we start from expressing the line as parametric over $t$: at $t = 0$ it's at point $M$ and at $t = 1$ it's at point $N$:

$$c = c_M + (c_N - c_M)t, t \in R, c \in \{x, y\}$$
$$c = c_M, t \in R, c \in \{x, y\}$$

Substituting $t$ in one of the equations we get:

$$(y_M - y_N)x + (x_N - x_M)y + (x_M y_N - x_N y_M) = 0$$

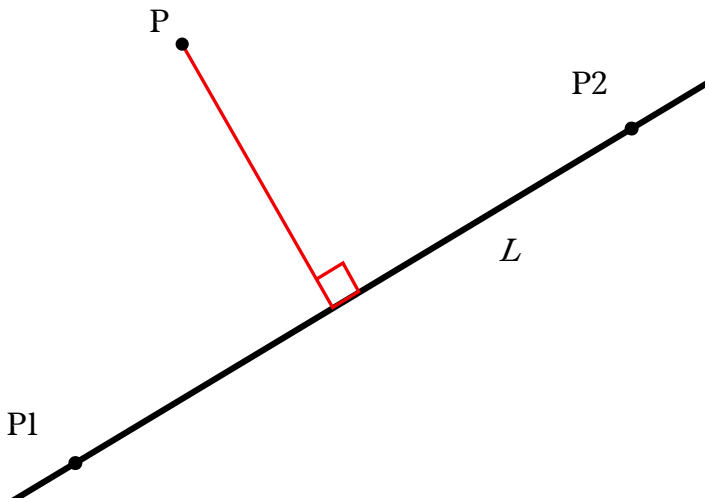
Which is what we were after. We finish by normalising what we found with $\frac{1}{\sqrt{a^2+b^2}}$:

# Chapter 7

# Distance from a point to a line



Add code samples in *Distance from a point to a line*




## 7.1 Using the implicit equation form

Let's find the distance from a given point $P$ and a given line $L$. Let $d$ be the distance between them. Bring $L$ to the implicit form $ax + by = c$.

$$d = \frac{|ax_p + by_p + c|}{\sqrt{a^2 + b^2}}$$

## 7.2 Using an $L$ defined by two points $P_1, P_2$

With $P = (x_0, y_0)$, $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$.

$$d = \frac{|(x_2 - x_1)(y_1 - y_0) - (x_1 - x_0)(y_2 - y_1)|}{\sqrt{((x_2 - x_1)^2 + (y_2 - y_1)^2}}$$

## 7.3 Using an $L$ defined by a point $P_l$ and angle $\theta$

$$d = |cos(\theta)(P_{ly} - y_p) - sin(\theta)(P_{lx} - P_x)|$$

# Chapter 8

# Angle between two lines



Add *Angle between two lines*

```
1
```

lines

# Chapter 9

# Intersection of two lines



Add *Intersection of two lines*

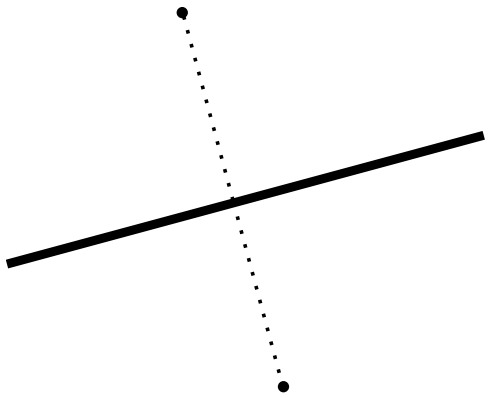
```
                                                                  2
```

lines

# Chapter 10

# Line equidistant from two points





Let's name this line $L$. From the previous chapter we know how to get the line that's created by the two points $M$ and $N$. If only we knew how to get a perpendicular line over the midpoint of a line segment!

Thankfully that midpoint also satisfies $L$'s equation, $ax+by+c$. The midpoint's coordinates are intuitively:

$$(\frac{x_M + x_N}{2}, \frac{y_M + y_N}{2})$$

Putting them into the equation we can generate a triple of $(a', b', c')$ and then normalize it to get $L$.

lines

# Chapter 11

# Normal to a line through a point



Add *Normal to a line through a point*

```
                                                                                3
```

lines

# Part III

# Points And Line Segments

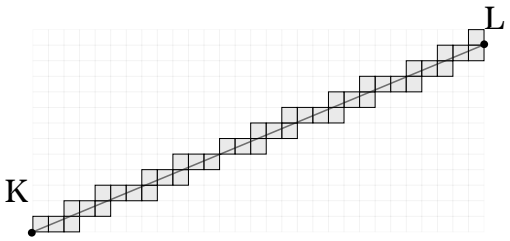
segments

# Chapter 12

# Drawing a line segment from its two endpoints



For any line segment with any slope, pixels must be matched with the infinite amount of points contained in the segment. As shown in the following figure, a segment *touches* some pixels; we could fill them using an algorithm and get a bitmap of the line segment.




The algorithm presented here was first derived by Bresenham. In the *Image* implementation, it is used in the `plot_line_width` method.

```
pub fn plot_line_width(&mut self, (x1, y1): (i64, i64), (x2, y2): (i64, i64)) {
    /* Bresenham's line algorithm */
    let mut d;
    let mut x: i64;
    let mut y: i64;
    let ax: i64;
    let ay: i64;
    let sx: i64;
    let sy: i64;
    let dx: i64;
    let dy: i64;

    dx = x2 - x1;
    ax = (dx * 2).abs();
    sx = if dx > 0 { 1 } else { -1 };
```

```
    dy = y2 - y1;
    ay = (dy * 2).abs();
    sy = if dy > 0 { 1 } else { -1 };

    x = x1;
    y = y1;

    let b = dx / dy;
    let a = 1;
    let double_d = (_wd * f64::sqrt((a * a + b * b) as f64)) as i64;
    let delta = double_d / 2;

    if ax > ay {
        d = ay - ax / 2;
        loop {
            self.plot(x, y);
            if x == x2 {
                return;
            }
            if d >= 0 {
                y = y + sy;
                d = d - ax;
            }
            x = x + sx;
            d = d + ay;
        }
    } else {
        d = ax - ay / 2;
        let delta = double_d / 3;
        loop {
            self.plot(x, y);
            if y == y2 {
                return;
            }
            if d >= 0 {
                x = x + sx;
                d = d - ay;
            }
            y = y + sy;
            d = d + ax;
        }
    }
}
```



Add some explanation behind the algorithm in *Drawing a line segment from its two endpoints*

# Chapter 13

# Drawing line segments with width

```
pub fn plot_line_width(&mut self, (x1, y1): (i64, i64), (x2, y2): (i64, i64), _wd: f64) {
    /* Bresenham's line algorithm */
    let mut d;
    let mut x: i64;
    let mut y: i64;
    let ax: i64;
    let ay: i64;
    let sx: i64;
    let sy: i64;
    let dx: i64;
    let dy: i64;

    dx = x2 - x1;
    ax = (dx * 2).abs();
    sx = if dx > 0 { 1 } else { -1 };

    dy = y2 - y1;
    ay = (dy * 2).abs();
    sy = if dy > 0 { 1 } else { -1 };

    x = x1;
    y = y1;

    let b = dx / dy;
    let a = 1;
    let double_d = (_wd * f64::sqrt((a * a + b * b) as f64)) as i64;
    let delta = double_d / 2;

    if ax > ay {
        d = ay - ax / 2;
        loop {
            self.plot(x, y);
            {
                let total = |_x| _x - (y * dx) / dy + (y1 * dx) / dy - x1;
                let mut _x = x;
                loop {
                    let t = total(_x);
                    if t < -1 * delta || t > delta {
                        break;
                    }
                    _x += 1;
                    self.plot(_x, y);
                }
                let mut _x = x;
                loop {
                    let t = total(_x);
                    if t < -1 * delta || t > delta {
                        break;
                    }
                    _x -= 1;
                    self.plot(_x, y);
                }
            }
```

```
            if x == x2 {
                return;
            }
            if d >= 0 {
                y = y + sy;
                d = d - ax;
            }
            x = x + sx;
            d = d + ay;
        }
    } else {
        d = ax - ay / 2;
        let delta = double_d / 3;
        loop {
            self.plot(x, y);
            {
                let total = |_x| _x - (y * dx) / dy + (y1 * dx) / dy - x1;
                let mut _x = x;
                loop {
                    let t = total(_x);
                    if t < -1 * delta || t > delta {
                        break;
                    }
                    _x += 1;
                    self.plot(_x, y);
                }
                let mut _x = x;
                loop {
                    let t = total(_x);
                    if t < -1 * delta || t > delta {
                        break;
                    }
                    _x -= 1;
                    self.plot(_x, y);
                }
            }
            if y == y2 {
                return;
            }
            if d >= 0 {
                x = x + sx;
                d = d - ay;
            }
            y = y + sy;
            d = d + ax;
        }
    }
}
```

# Chapter 14

# Intersection of two line segments

Let points **1** $= (x_1, y_1)$, **2** $= (x_2, y_2)$, **3** $= (x_3, y_3)$ and **4** $= (x_4, y_4)$ and **1**,**2**, **3**,**4** two line segments they form. We wish to find their intersection:

First, get the equation of line $L_{12}$ and line $L_{34}$ from chapter *Equations of a line*.

Substitute points **3** and **4** in equation $L_{12}$ to compute $r_3 = L_{12}(\mathbf{3})$ and $r_4 = L_{12}(\mathbf{4})$ respectively.

If $r_3 \neq 0$, $r_4 \neq 0$ and $sgn(r_3) == sign(r_4)$ the line segments don't intersect, so stop.

In $L_{34}$ substitute point **1** to compute $r_1$, and do the same for point **2**.

If $r_1 \neq 0$, $r_2 \neq 0$ and $sgn(r_1) == sign(r_2)$ the line segments don't intersect, so stop.

At this point, $L_{12}$ and $L_{34}$ either intersect or are equivalent. Find their intersection point. (Refer to *Intersection of two lines*.)

Add code sample in *Intersection of two line segments*

## 14.1 *Fast* intersection of two line segments

```
4
```

segments

circles

# Part IV

# Points, Lines and Circles

circles

5

# Chapter 15

# Equations of a circle

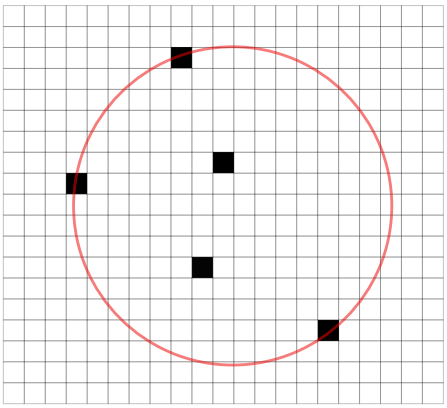
Add *Equations of a circle*

6

circles

# Chapter 16

# Bounding circle



src/bin/boundingcircle.rs:

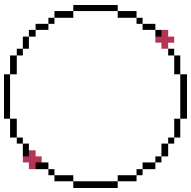
This code file is a PDF attachment

circles

A bounding circle is a circle that includes all the points in a given set. Usually we're interested in one of the smallest ones possible.

We can use the following methodology to find the bounding circle: start from two points and the circle they make up, and for each of the rest of the points check if the circle includes them. If not, make a bounding circle that includes every point up to the current one. To do this, we need some primitive operations.

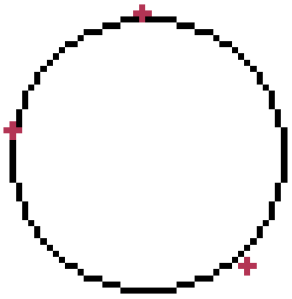
We will need a way to construct a circle out of two points:



```
  let p1 = points[0];
  let p2 = points[1];
  //The circle is determined by two points, P and Q. The center of the circle
  ↪ is
  //at (P + Q)/2.0 and the radius is |(P - Q)/2.0|
  let d_2 = (
  (((p1.0 + p2.0) / 2), (p1.1 + p2.1) / 2),
  (distance_between_two_points(p1, p2) / 2.0),
  );
```

And a way to make a circle out of three points:





```
fn min_circle_w_3_points(q1: Point, q2: Point, q3: Point) -> Circle {
    let (ax, ay) = (q1.0 as f64, q1.1 as f64);
    let (bx, by) = (q2.0 as f64, q2.1 as f64);
    let (cx, cy) = (q3.0 as f64, q3.1 as f64);

    let mut d = 2. * (ax * (by - cy) + bx * (cy - ay) + cx * (ay - by));
    if d == 0.0 {
        d = std::cmp::max(
            std::cmp::max(
                distance_between_two_points(q1, q2) as i64,
                distance_between_two_points(q2, q3) as i64,
            ),
            distance_between_two_points(q1, q3) as i64,
        ) as f64
            / 2.;
    }
    let ux = ((ax * ax + ay * ay) * (by - cy)
        + (bx * bx + by * by) * (cy - ay)
        + (cx * cx + cy * cy) * (ay - by))
        / d;
    let uy = ((ax * ax + ay * ay) * (cx - bx)
```

```
        + (bx * bx + by * by) * (ax - cx)
        + (cx * cx + cy * cy) * (bx - ax))
        / d;
    let mut center = (ux as i64, uy as i64);

    if center.0 < 0 {
        center.0 = 0;
    }
    if center.1 < 0 {
        center.1 = 0;
    }
    let d = distance_between_two_points(center, q1);
    (center, d)
}
```

The algorithm:

```
use bitmappers_companion::*;
use minifb::{Key, Window, WindowOptions};
use rand::seq::SliceRandom;
use rand::thread_rng;
use std::f64::consts::{FRAC_PI_2, PI};

include!("../me.xbm.rs");

const WINDOW_WIDTH: usize = 400;
const WINDOW_HEIGHT: usize = 400;

pub fn distance_between_two_points(p_k: Point, p_l: Point) -> f64 {
    let (x_k, y_k) = p_k;
    let (x_l, y_l) = p_l;
    let xlk = x_l - x_k;
    let ylk = y_l - y_k;
    f64::sqrt((xlk * xlk + ylk * ylk) as f64)
}

fn image_to_points(image: &Image) -> Vec<Point> {
    let mut ret = Vec::with_capacity(image.bytes.len());
    for y in 0..(image.height as i64) {
        for x in 0..(image.width as i64) {
            if image.get(x, y) == Some(BLACK) {
                ret.push((x, y));
            }
        }
    }
    ret
}

type Circle = (Point, f64);

fn bc(image: &Image) -> Circle {
    let mut points = image_to_points(image);
    points.shuffle(&mut thread_rng());
    min_circle(&points)
}
fn min_circle(points: &[Point]) -> Circle {
    let mut points = points.to_vec();
    points.shuffle(&mut thread_rng());

    let p1 = points[0];
    let p2 = points[1];
    //The circle is determined by two points, P and Q. The center of the
↪   circle is
    //at (P + Q)/2.0 and the radius is |(P - Q)/2.0|
    let d_2 = (
        (((p1.0 + p2.0) / 2), (p1.1 + p2.1) / 2),
        (distance_between_two_points(p1, p2) / 2.0),
    );

    let mut d_prev = d_2;

    for i in 2..points.len() {
        let p_i = points[i];
        if distance_between_two_points(p_i, d_prev.0) <= (d_prev.1) {
            // then d_i = d_(i-1)
```

```
        } else {
            let new = min_circle_w_point(&points[..i], p_i);
            if distance_between_two_points(p_i, new.0) <= (new.1) {
                d_prev = new;
            }
        }
    }

    d_prev
}

fn min_circle_w_point(points: &[Point], q: Point) -> Circle {
    let mut points = points.to_vec();

    points.shuffle(&mut thread_rng());
    let p1 = points[0];
    //The circle is determined by two points, P_1 and Q. The center of the
↪   circle is
    //at (P_1 + Q)/2.0 and the radius is |(P_1 - Q)/2.0|
    let d_1 = (
        (((p1.0 + q.0) / 2), (p1.1 + q.1) / 2),
        (distance_between_two_points(p1, q) / 2.0),
    );

    let mut d_prev = d_1;

    for j in 1..points.len() {
        let p_j = points[j];
        if distance_between_two_points(p_j, d_prev.0) <= (d_prev.1) {
            //d_prev = d_prev;
        } else {
            let new = min_circle_w_points(&points[..j], p_j, q);
            if distance_between_two_points(p_j, new.0) <= (new.1) {
                d_prev = new;
            }
        }
    }
    d_prev
}

fn min_circle_w_points(points: &[Point], q1: Point, q2: Point) -> Circle {
    let mut points = points.to_vec();

    let d_0 = (
        (((q1.0 + q2.0) / 2), (q1.1 + q2.1) / 2),
        (distance_between_two_points(q1, q2) / 2.0),
    );

    let mut d_prev = d_0;
    for k in 0..points.len() {
        let p_k = points[k];
        if distance_between_two_points(p_k, d_prev.0) <= (d_prev.1) {
        } else {
            let new = min_circle_w_3_points(q1, q2, p_k);
            if distance_between_two_points(p_k, new.0) <= (new.1) {
                d_prev = new;
            }
        }
    }
    d_prev
}

fn min_circle_w_3_points(q1: Point, q2: Point, q3: Point) -> Circle {
    let (ax, ay) = (q1.0 as f64, q1.1 as f64);
    let (bx, by) = (q2.0 as f64, q2.1 as f64);
    let (cx, cy) = (q3.0 as f64, q3.1 as f64);

    let mut d = 2. * (ax * (by - cy) + bx * (cy - ay) + cx * (ay - by));
    if d == 0.0 {
        d = std::cmp::max(
            std::cmp::max(
                distance_between_two_points(q1, q2) as i64,
                distance_between_two_points(q2, q3) as i64,
            ),
            distance_between_two_points(q1, q3) as i64,
        ) as f64
            / 2.;
    }
```

```
    let ux = ((ax * ax + ay * ay) * (by - cy)
        + (bx * bx + by * by) * (cy - ay)
        + (cx * cx + cy * cy) * (ay - by))
        / d;
    let uy = ((ax * ax + ay * ay) * (cx - bx)
        + (bx * bx + by * by) * (ax - cx)
        + (cx * cx + cy * cy) * (bx - ax))
        / d;
    let mut center = (ux as i64, uy as i64);

    if center.0 < 0 {
        center.0 = 0;
    }
    if center.1 < 0 {
        center.1 = 0;
    }
    let d = distance_between_two_points(center, q1);
    (center, d)
}

fn main() {
    let mut buffer: Vec<u32> = vec![WHITE; WINDOW_WIDTH * WINDOW_HEIGHT];
    let mut window = Window::new(
        "Test - ESC to exit",
        WINDOW_WIDTH,
        WINDOW_HEIGHT,
        WindowOptions {
            title: true,
            //borderless: true,
            resize: true,
            //transparency: true,
            ..WindowOptions::default()
        },
    )
    .unwrap();

    // Limit to max ~60 fps update rate
    window.limit_update_rate(Some(std::time::Duration::from_micros(16600)));

    let mut full = Image::new(WINDOW_WIDTH, WINDOW_HEIGHT, 0, 0);
    let mut image = Image::new(ME_WIDTH, ME_HEIGHT, 45, 45);
    image.bytes = bits_to_bytes(ME_BITS, ME_WIDTH);
    let (center, r) = bc(&image);
    image.draw_outline();

    full.plot_circle((center.0 + 45, center.1 + 45), r as i64, 0.);
    while window.is_open() && !window.is_key_down(Key::Escape) &&
↪   !window.is_key_down(Key::Q) {
        image.draw(&mut buffer, BLACK, None, WINDOW_WIDTH);
        full.draw(&mut buffer, BLACK, None, WINDOW_WIDTH);

        window
            .update_with_buffer(&buffer, WINDOW_WIDTH, WINDOW_HEIGHT)
            .unwrap();

        let millis = std::time::Duration::from_millis(100);

        std::thread::sleep(millis);
    }
}
```

curves

# Part V

# Curves other than circles

curves

# Chapter 17

# Parametric elliptical arcs

Add *Parametric elliptical arcs*

7

curves

# Part VI

# Points, Lines and Shapes

shapes

# Chapter 18

# Union, intersection and difference of polygons

Add *Union, intersection and difference of polygons*

```
8
```

shapes

# Chapter 19

# Centroid of polygon

Add *Centroid of polygon*

```
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```

shapes

# Chapter 20

# Flood filling

Add *Flood filling*

10

shapes

# Part VII

# Vectors, matrices and transformations

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forma-
tions

# Chapter 21

# Rotation of a bitmap

$$p' = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} x_p \\ y_p \end{bmatrix}$$

$$c = cos\theta, s = sin\theta, x_{p'} = x_p c - y_p s, y_{p'} = x_p s + y_p c.$$

Let's load an `xface`. We will use `bits_to_bytes` (See Introduction).

src/bin/rotation.rs:

This code file is a PDF attachment

```
include!("dmr.rs");

const WINDOW_WIDTH: usize = 100;
const WINDOW_HEIGHT: usize = 100;

let mut image = Image::new(DMR_WIDTH, DMR_HEIGHT, 25, 25);
image.bytes = bits_to_bytes(DMR_BITS, DMR_WIDTH);
```


This is the `xface` of `dmr`. Instead of displaying the bitmap, this time we will rotate it 0.5 radians. Setup our image first:

```
let mut image = Image::new(DMR_WIDTH, DMR_HEIGHT, 25, 25);
image.draw_outline();
let dmr = bits_to_bytes(DMR_BITS, DMR_WIDTH);
```

And then, loop for each byte in `dmr`'s face and apply the rotation transformation.

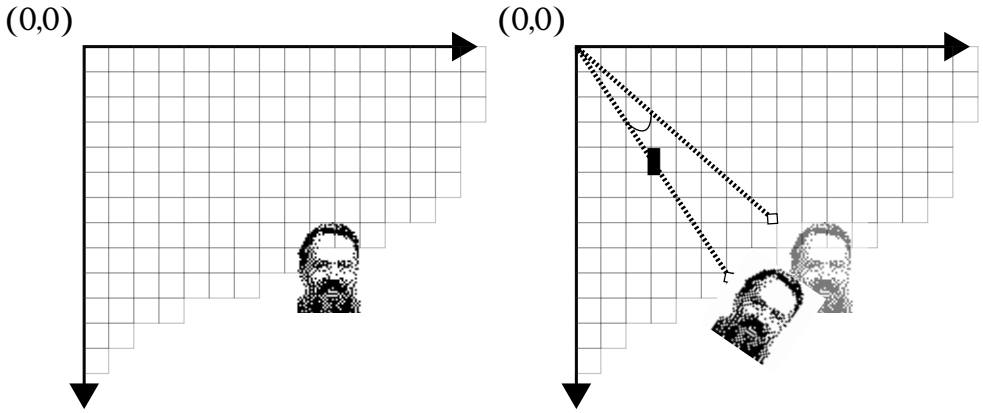
```
let angle = 0.5;

let c = f64::cos(angle);
let s = f64::sin(angle);

for y in 0..DMR_HEIGHT {
    for x in 0..DMR_WIDTH {
        if dmr[y * DMR_WIDTH + x] == BLACK {
            let x = x as f64;
            let y = y as f64;
            let xr = x * c - y * s;
            let yr = x * s + y * c;
            image.plot(xr as i64, yr as i64);
        }
    }
}
```

The result:


We didn't mention in the beginning that the rotation has to be relative to a *point* and the given transformation is relative to the *origin*, in this case the upper left corner $(0, 0)$. So `dmr` was rotated relative to the origin:




(the distance to the origin (actually 0 pixels) has been exaggerated for the sake of the example)

Usually, we want to rotate something relative to itself. The right point to choose is the *centroid* of the object.

If we have a list of $n$ points, the centroid is calculated as:

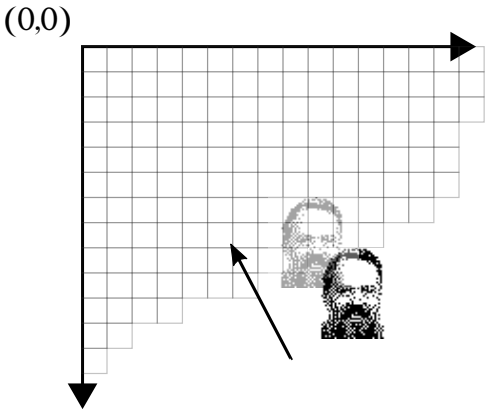
$$x_c = \frac{1}{n}\sum_{i=0}^{n} x_i$$

$$y_c = \frac{1}{n}\sum_{i=0}^{n} y_i$$

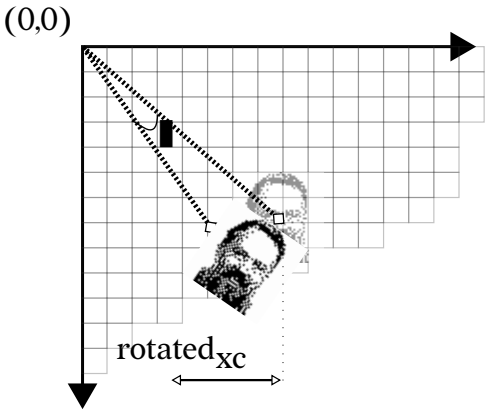
Since in this case we have a rectangle, the centroid has coordinates of half the width and half the height.

By subtracting the centroid from each point before we apply the transformation and then adding it back after we get what we want:

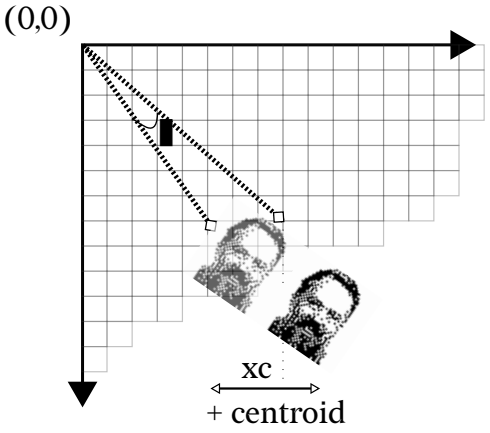
Here's it visually: First subtract the center point.




Then, rotate.




And subtract back to the original position.



In code:

```
let center_point = ((DMR_WIDTH/2) as i64, (DMR_HEIGHT/2) as i64);
for y in 0..DMR_HEIGHT {
    for x in 0..DMR_WIDTH {
        if dmr[y * DMR_WIDTH + x] == BLACK {
            let x = (x as i64 -center_point.0) as f64;
            let y = (y as i64 -center_point.1) as f64;
            let xr = x * c - y * s;
            let yr = x * s + y * c;
            image.plot(xr as i64+center_point.0,
                       yr as i64 + center_point.1);
        }
    }
}
```

The result: 


## 21.1 Fast 2D Rotation

Add *Fast 2D Rotation*

ll

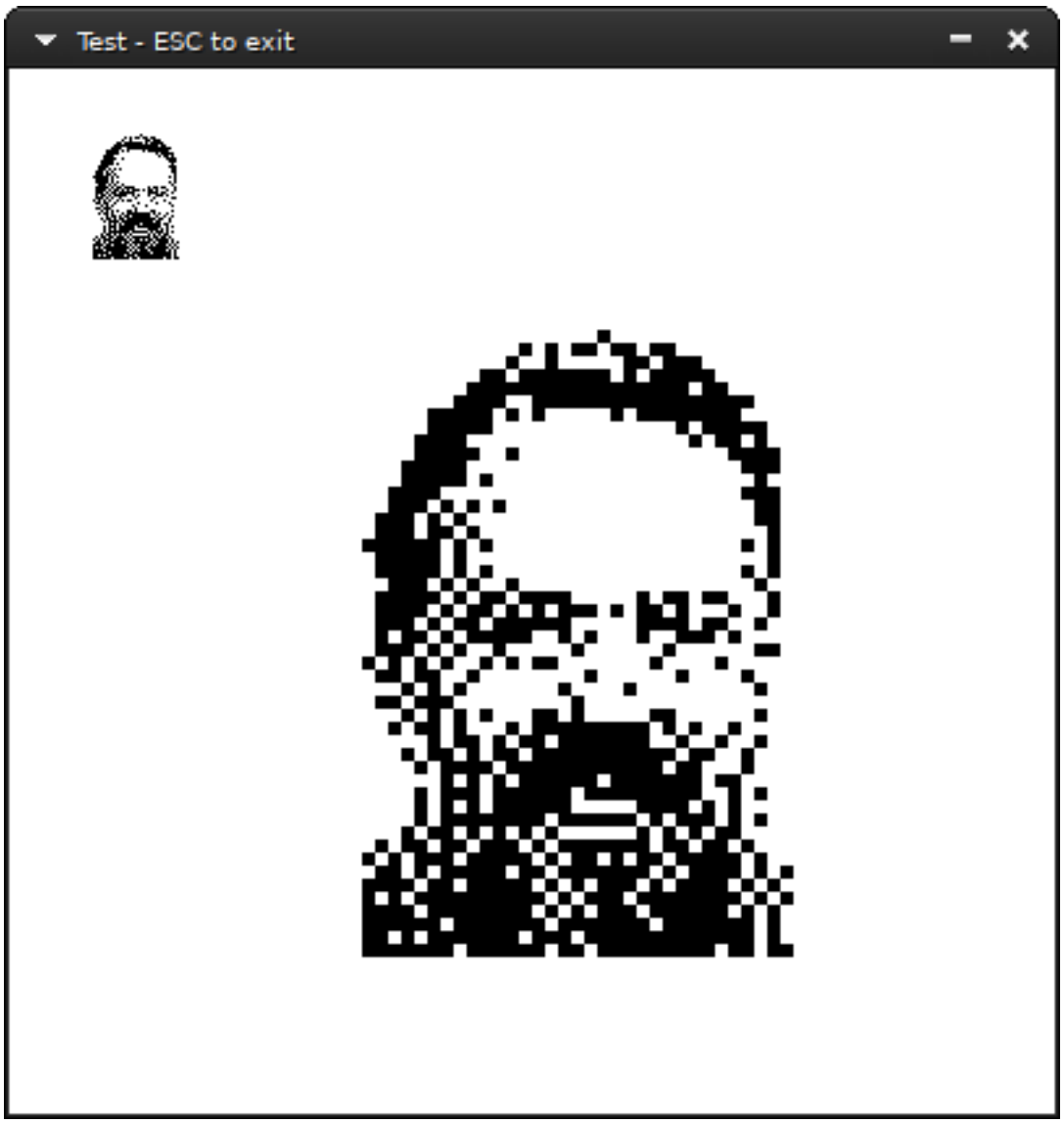
# Chapter 22

# 90° Rotation of a bitmap by parallel recursive subdivision

Add *90° Rotation of a bitmap by parallel recursive subdivision*

# Chapter 23

# Magnification/Scaling



src/bin/scale.rs:

This code file is a PDF attachment

```
let mut original = Image::new(DMR_WIDTH, DMR_HEIGHT, 25, 25);
original.bytes = bits_to_bytes(DMR_BITS, DMR_WIDTH);
original.draw(&mut buffer, BLACK, None, WINDOW_WIDTH);

let mut scaled = Image::new(DMR_WIDTH * 5, DMR_HEIGHT * 5, 100, 100);
let mut sx: i64; //source
let mut sy: i64; //source
let mut dx: i64; //destination
let mut dy: i64 = 0; //destination

let og_height = original.height as i64;
let og_width = original.width as i64;
let scaled_height = scaled.height as i64;
let scaled_width = scaled.width as i64;

while dy < scaled_height {
    sy = (dy * og_height) / scaled_height;
    dx = 0;
    while dx < scaled_width {
        sx = (dx * og_width) / scaled_width;
        if original.get(sx, sy) == Some(BLACK) {
            scaled.plot(dx, dy);
        }
        dx += 1;
    }
    dy += 1;
}
scaled.draw(&mut buffer, BLACK, None, WINDOW_WIDTH);
```

## 23.1 Smoothing enlarged bitmaps

Add *Smoothing enlarged bitmaps*

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## 23.2 Stretching lines of bitmaps

Add *Stretching lines of bitmaps*

# Chapter 24

# Mirroring

Add screenshots and figure and code in *Mirroring*

Mirroring to an axis is the transformation of one coordinate to its equidistant value across the axis:

To mirror a pixelacross the $x$ axis, simply multiply its coordinates with the following matrix:

$$M_x = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

This results in the $y$ coordinate's sign being flipped.

For $y$-mirroring, the transformation follows the same logic:

$$M_y = \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}$$

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tions

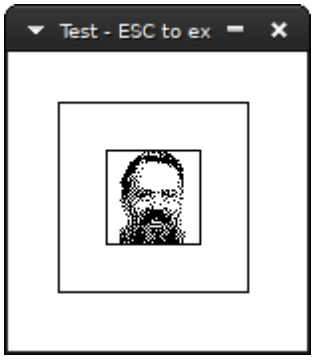
# Chapter 25

# Shearing

Simple shearing is the transformation of one dimension by a distance proportional to the other dimension, In $x$-shearing (or horizontal shearing) only the $x$ coordinate is affected, and likewise in $y$-shearing only $y$ as well.

src/bin/shearing.rs:

This code file is a PDF attachment

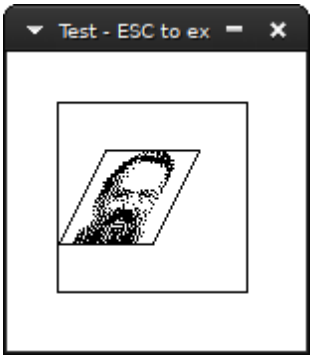



With $l$ being equal to the desired tilt away from the $y$ axis, the transformation is described by the following matrix:

$$S_x = \begin{bmatrix} 1 & l \\ 0 & 1 \end{bmatrix}$$

Which is as simple as this function:

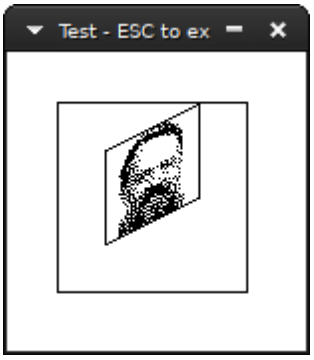
```
fn shear_x((x_p, y_p): (i64, i64), l: f64) -> (i64, i64) {
    (x_p+(l*(y_p as f64)) as i64, y_p)
}
```




For $y$-shearing, we have the following:

$$S_y = \begin{bmatrix} 1 & 0 \\ l & 1 \end{bmatrix}$$

```
fn shear_y((x_p, y_p): (i64, i64), l: f64) -> (i64, i64) {
    (x_p, (l*(x_p as f64)) as i64 + y_p)
}
```



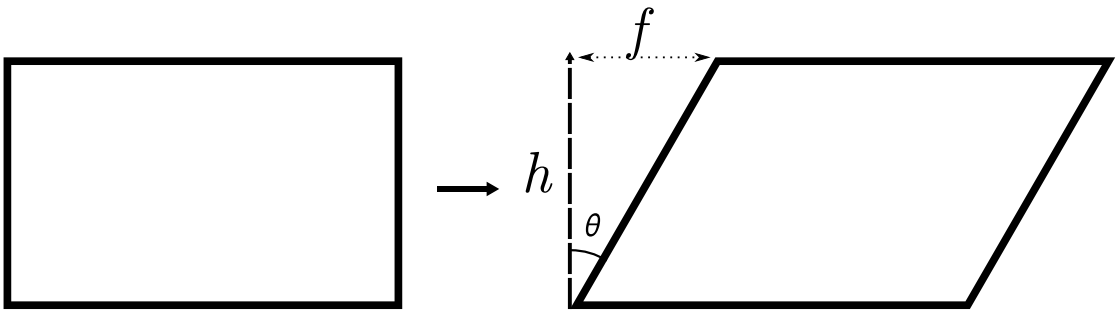



A full example:

```
include!("../dmr.xbm.rs");

const WINDOW_WIDTH: usize = 200;
const WINDOW_HEIGHT: usize = 200;

fn shear_x((x_p, y_p): (i64, i64), l: f64) -> (i64, i64) {
    (x_p+(l*(y_p as f64)) as i64, y_p)
}
fn shear_y((x_p, y_p): (i64, i64), l: f64) -> (i64, i64) {
    (x_p, (l*(x_p as f64)) as i64 + y_p)
}

let mut image = Image::new(DMR_WIDTH, DMR_HEIGHT, 25, 25);
image.bytes = bits_to_bytes(DMR_BITS, DMR_WIDTH);
image.draw_outline();
```

```
let l = -0.5;
let mut sheared = Image::new(DMR_WIDTH*2, DMR_HEIGHT*2, 25, 25);
for x in 0..DMR_WIDTH {
    for y in 0..DMR_HEIGHT  {
        if image.bytes[y * DMR_WIDTH + x] == BLACK {
          let p = shear_x((x as i64 ,y as i64 ), l);
          sheared.plot(p.0+(DMR_WIDTH/2) as i64, p.1+(DMR_HEIGHT/2) as i64);
        }
    }
}
sheared.draw_outline();
```

## 25.1 The relationship between shearing factor and angle




Shearing is a delta movement in one dimension, thus the point before moving and the point after form an angle with the $x$ axis. To move a point $(x,0)$ by 30° forward we will have the new point $(x+f,0)$ where $f$ is the shear factor. These two points and $(x,h)$ where $h$ is the height of the bitmap form a triangle, thus the following are true:

$$cot\theta = \frac{h}{f}$$

Therefore to find your factor for any angle $\theta$ replace its cotangent in the following formula:

$$f = \frac{h}{cot\theta}$$

For example to shear by $-30°$ (meaning the bitmap will move to the right, since rotations are always clockwise) we need $cot(-30deg) = -\sqrt{3}$ and $f = -\frac{h}{\sqrt{3}}$.

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tions

# Chapter 26

# Projections

Add *Projections*

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# Part VIII

# Addendum

addendum

# 26.1 Faster Drawing a line segment from its two endpoints using Symmetry

Add *Faster Drawing a line segment from its two endpoints using Symmetry*

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addendum

addendum

# Chapter 27

# Joining the ends of two wide line segments together

Add *Joining the ends of two wide line segments together*

17

addendum

# Chapter 28

# Composing monochrome bitmaps with separate alpha channel data

Add *Composing monochrome bitmaps with separate alpha channel data* 18

addendum

# Chapter 29

# Orthogonal connection of two points

Add *Orthogonal connection of two points*

19

addendum

# Chapter 30

# Join segments with round corners

Add *Join segments with round corners*

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addendum

# Chapter 31

# Faster line clipping

Add *Faster line clipping*

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addendum

# Chapter 32

# Space-filling Curves

Add *Space-filling Curves*

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## 32.1 Hilbert curves

Add *Hilbert curves*

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addendum

## 32.2 Peano curves

Add *Peano curves*

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## 32.3 Z-order curves

Add *Z-order curves*

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addendum

# Index

# About this text

The text has been typeset in XeLaTeX using the `book` class and:

- **Redaction** for the main text.
- **Fira Sans** for referring to the programming language **Rust**.
- **Redaction20** for referring to the words bitmap and pixels as a concept.

# Todo list