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# A Bitmapper's Companion

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epilys

November 28, 2021

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**

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The source code is available here

<https://github.com/epilys/bitmappers-companion>

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# Part I

## Introduction



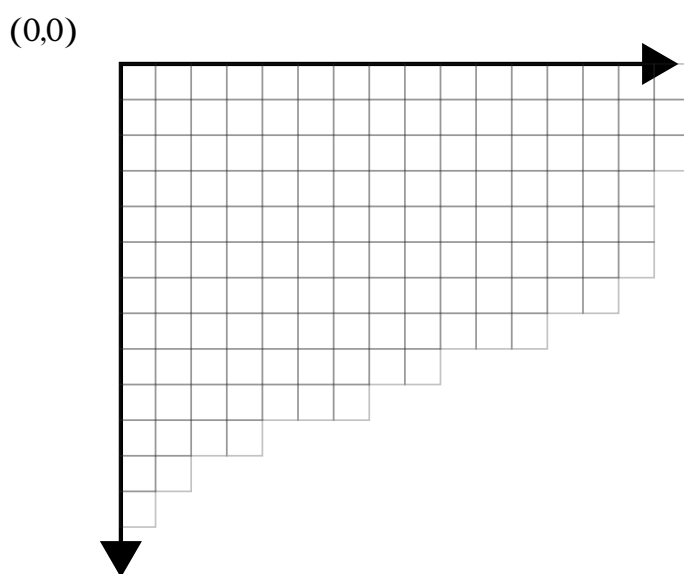


## Chapter 1

# 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 l 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 ignored (clipped).



```

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;

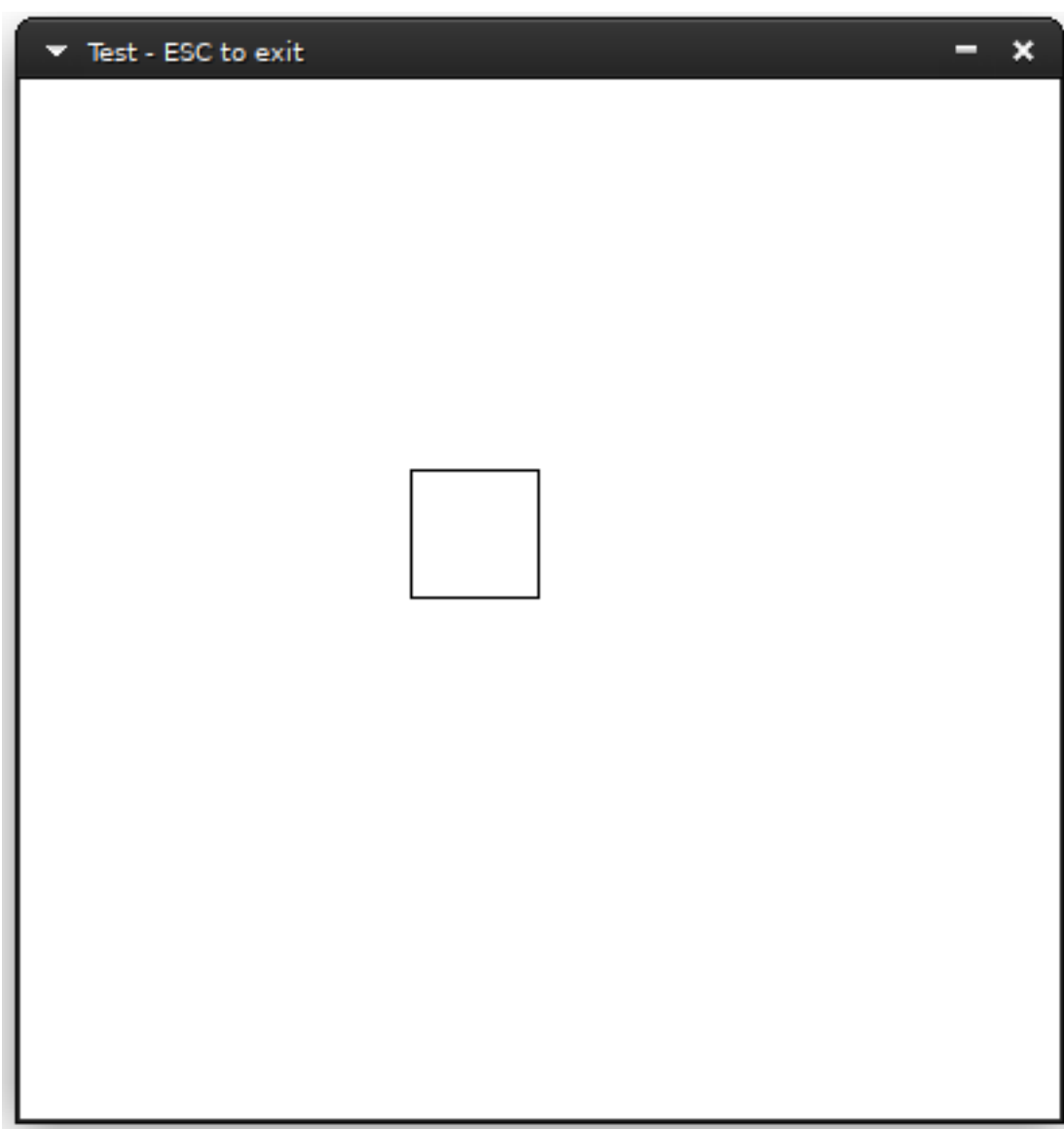
fn main() {
    let mut buffer: Vec<u32> = vec![WHITE; WINDOW_WIDTH * WINDOW_HEIGHT];
    let mut window = Window::new(
        "Test - ESC to exit",
        WINDOW_WIDTH,
        WINDOW_HEIGHT,
        WindowOptions {
            title: true,
            //borderless: true,
            //resize: false,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



## 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  
}
```



# Chapter 4

## Real pixels to byte pixels

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1

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## Chapter 5

# Loading xbm files in Rust

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 `]`.

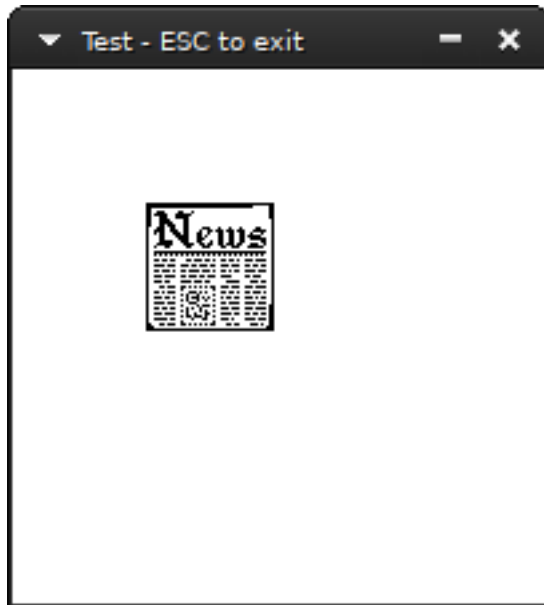
We can then include the new file in our source code:

```
| 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:



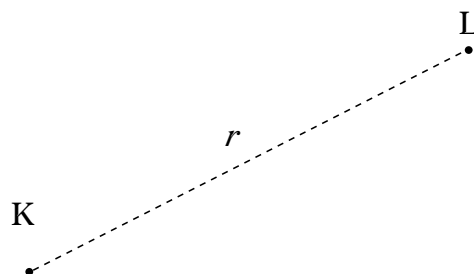
# **Part II**

## **Points And Lines**

lines

## Chapter 6

# Distance between two points



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

$$r = \sqrt{(x_L - x_K)^2 + (y_L - y_K)^2} \quad (6.1)$$

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 x_lk = x_l - x_k;  
  let y_lk = y_l - y_k;  
  f64::sqrt((x_lk*x_lk + y_lk*y_lk) as f64)  
}
```

lines

## Chapter 7

# 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...

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

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

## 7.2 Line through two points

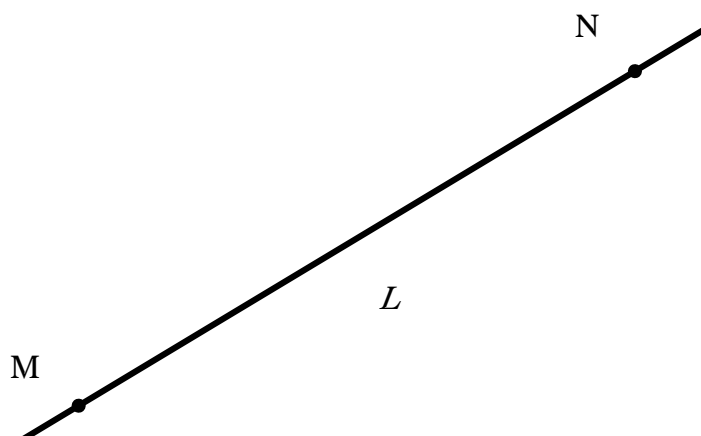


Figure 7.1:

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  $N$ :

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

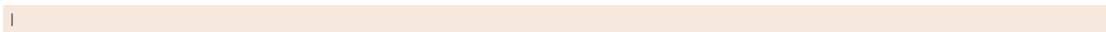
$$c = c_M, t \in R, c \in \{x, y\}$$

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  $\frac{1}{\sqrt{a^2 + b^2}}$ :

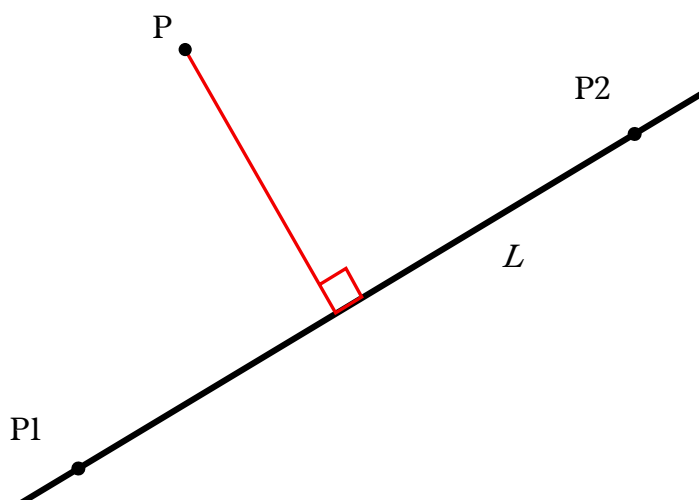




lines

## Chapter 8

# Distance from a point to a line



### 8.1 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  $ax + by = c$ .

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

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

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

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

### 8.3 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 9

# Angle between two lines

2

lines



## Chapter 10

# Intersection of two lines

3

lines





## Chapter 11

# Line equidistant from two points

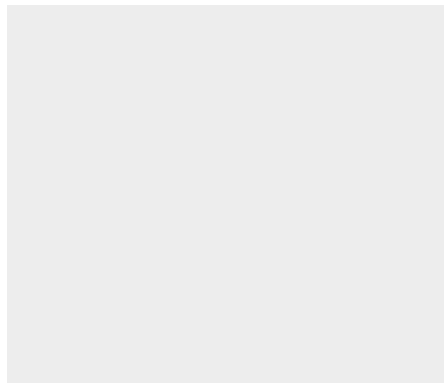


Figure 11.1:

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:

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

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

lines

## Chapter 12

# Normal to a line through a point

6

lines



## **Part III**

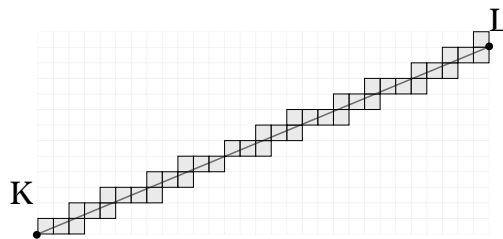
# **Points And Line Segments**

segment

## Chapter 13

# 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();
```

segment

```

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;
  }
}
}
```



## Chapter 14

# 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);  
                }  
            }  
        }  
    }
```

segment

```
        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 15

## 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*.)

### 15.1 Fast intersection of two line segments

7

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[Redacted text block 2]

[Redacted text block 3]

[Redacted text block 4]



segment



# **Part IV**

## **Points, Lines and Circles**





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[Redacted text block 2]

[Redacted text block 3]

[Redacted text block 4]



## Chapter 16

# Equations of a circle

circles

9

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## Chapter 17

# Bounding circle

circles

10

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## Part V

# Curves other than circles





## Chapter 18

# Parametric elliptical arcs



11

curves

[Redacted text block]

[Redacted text block]

[Redacted text block]

## **Part VI**

# **Points, Lines and Shapes**

shapes



## Chapter 19

# Union, intersection and difference of polygons

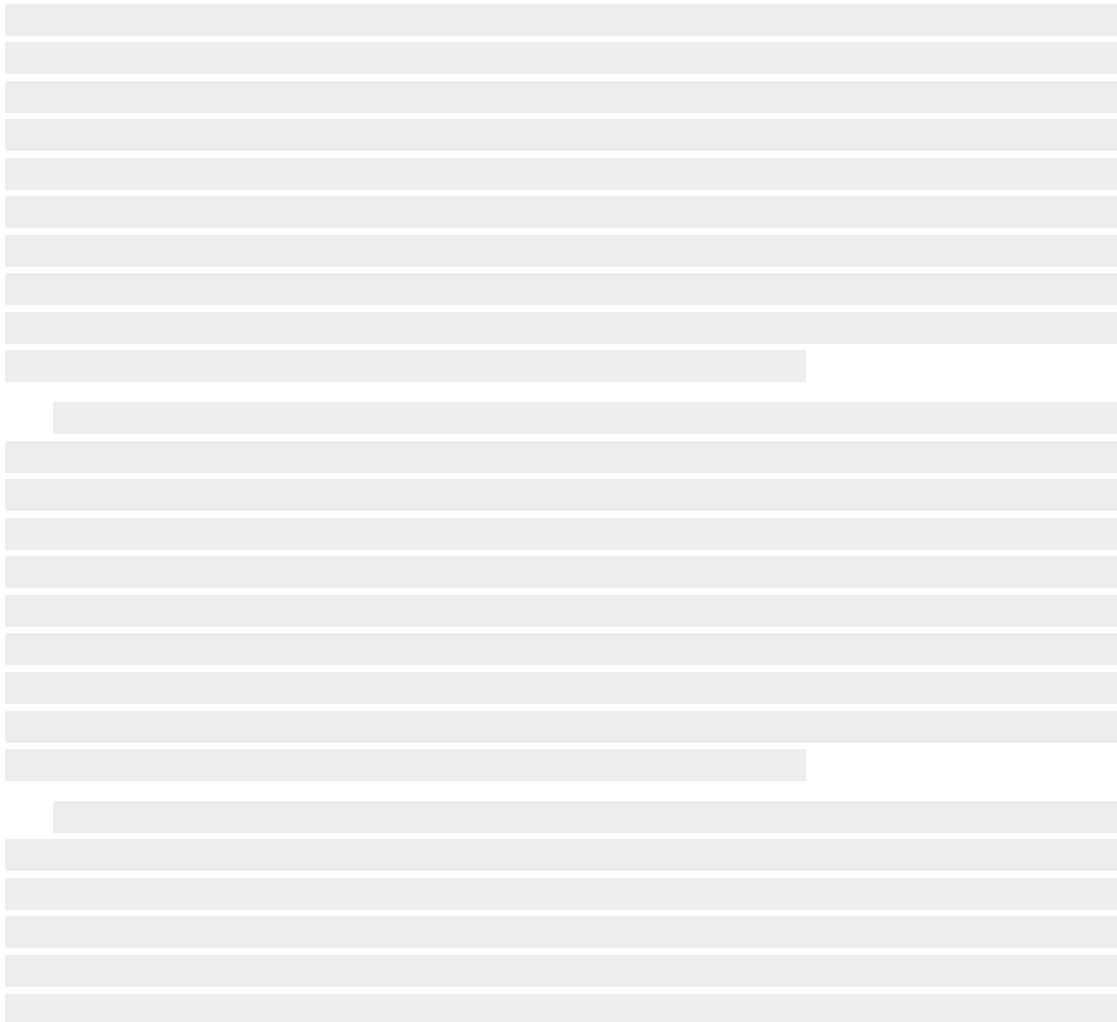
12

# shapes



## Chapter 20

# Centroid of polygon



13

shapes





## Chapter 21

# Flood filling



14

shapes





shapes







## Part VII

# Vectors, matrices and transformations

trans-  
forma-  
tions





## Chapter 22

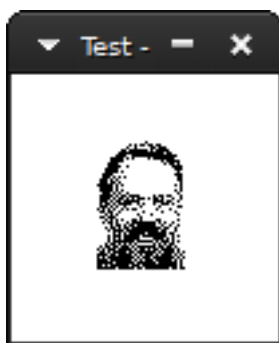
# Rotation of a bitmap

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

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

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

```
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:

src/bin/rotation



This code file is a PDF attachment

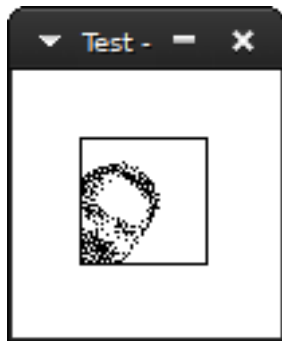
trans-  
forma-  
tions

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

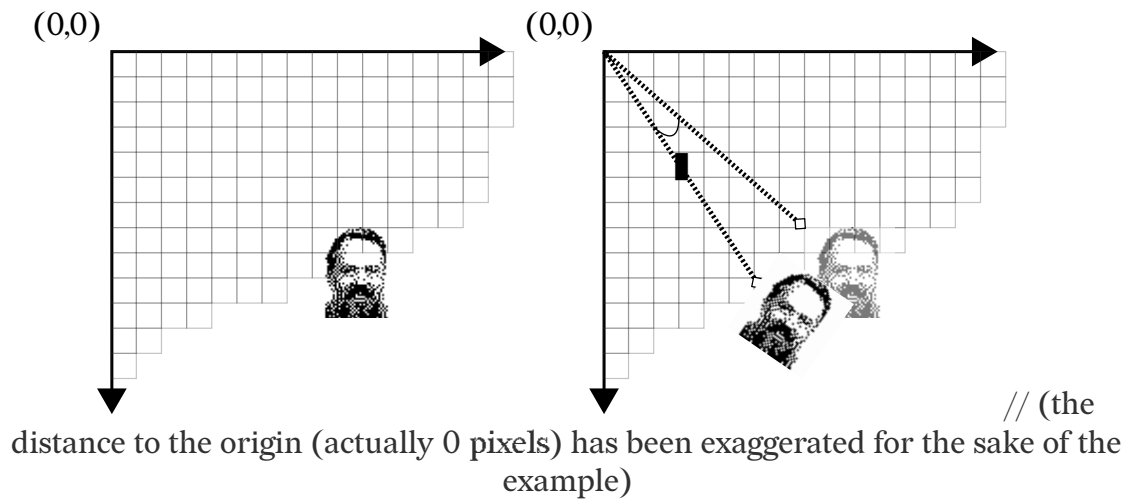
And then, loop for each byte in dmr's face and apply the rotation transformation.

```
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:



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:

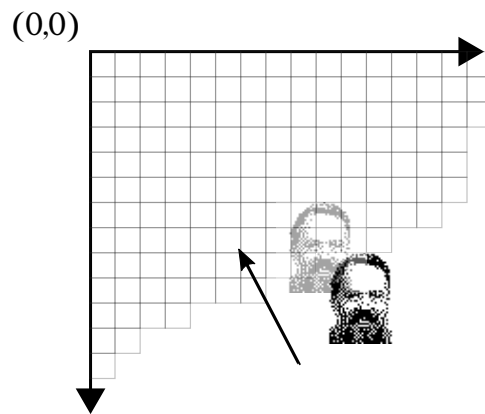
$$x_c = \frac{1}{n} \sum_{i=0}^n x_i$$

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

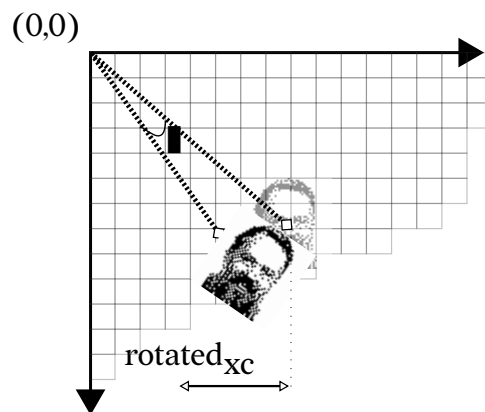
Since in this case we have a rectangle, the centroid has coordinates of half the width and half the height.

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

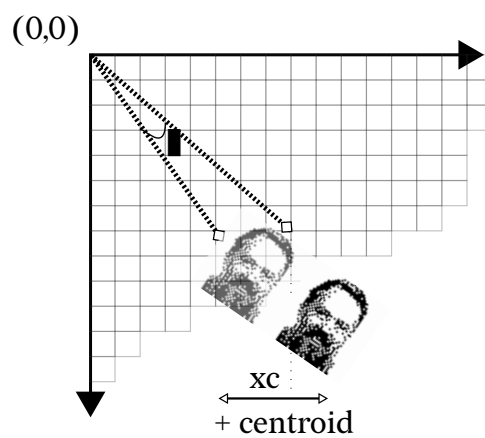
Here's it visually: First subtract the center point.



Then, rotate.

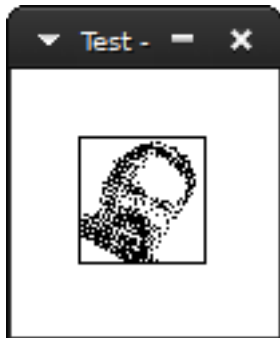


And subtract back to the original position.



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:

## 22.1 Fast 2D Rotation

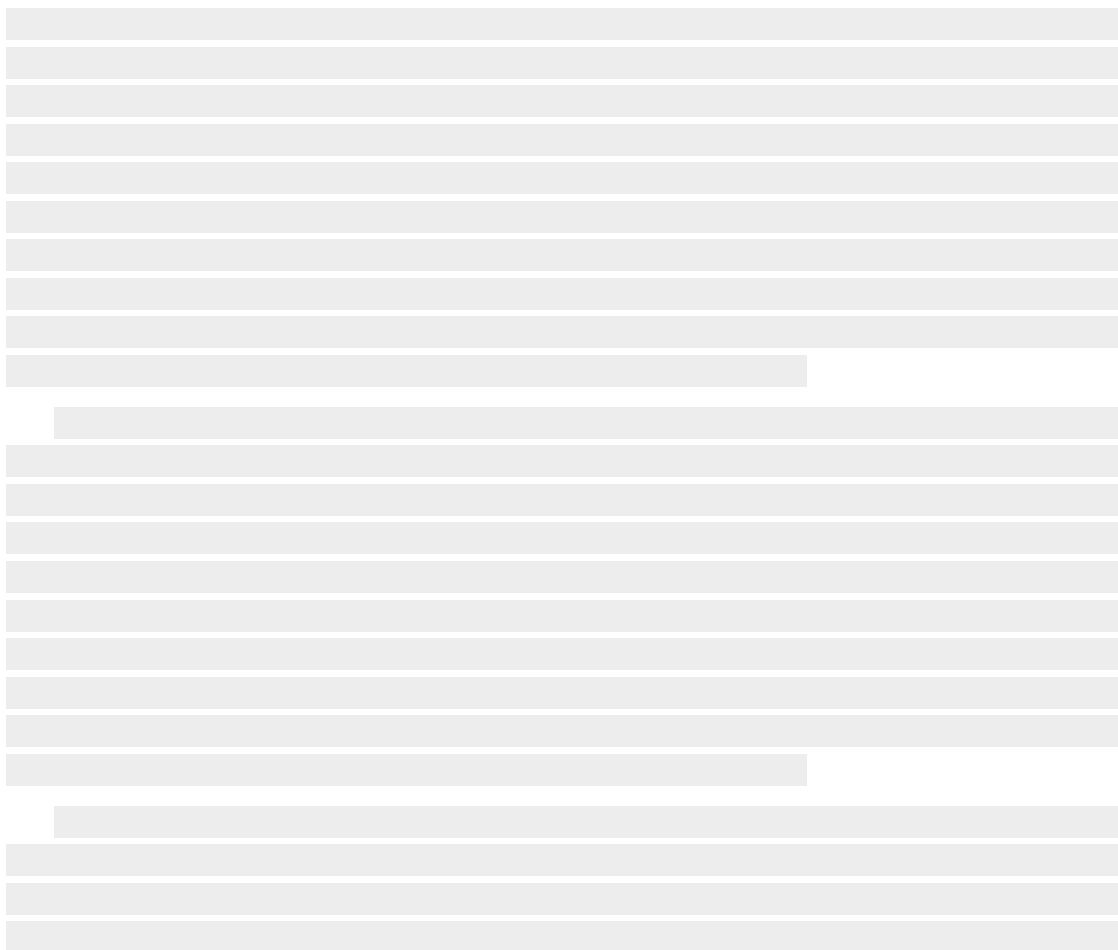
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## Chapter 23

# 90° Rotation of a bitmap by parallel recursive subdivision



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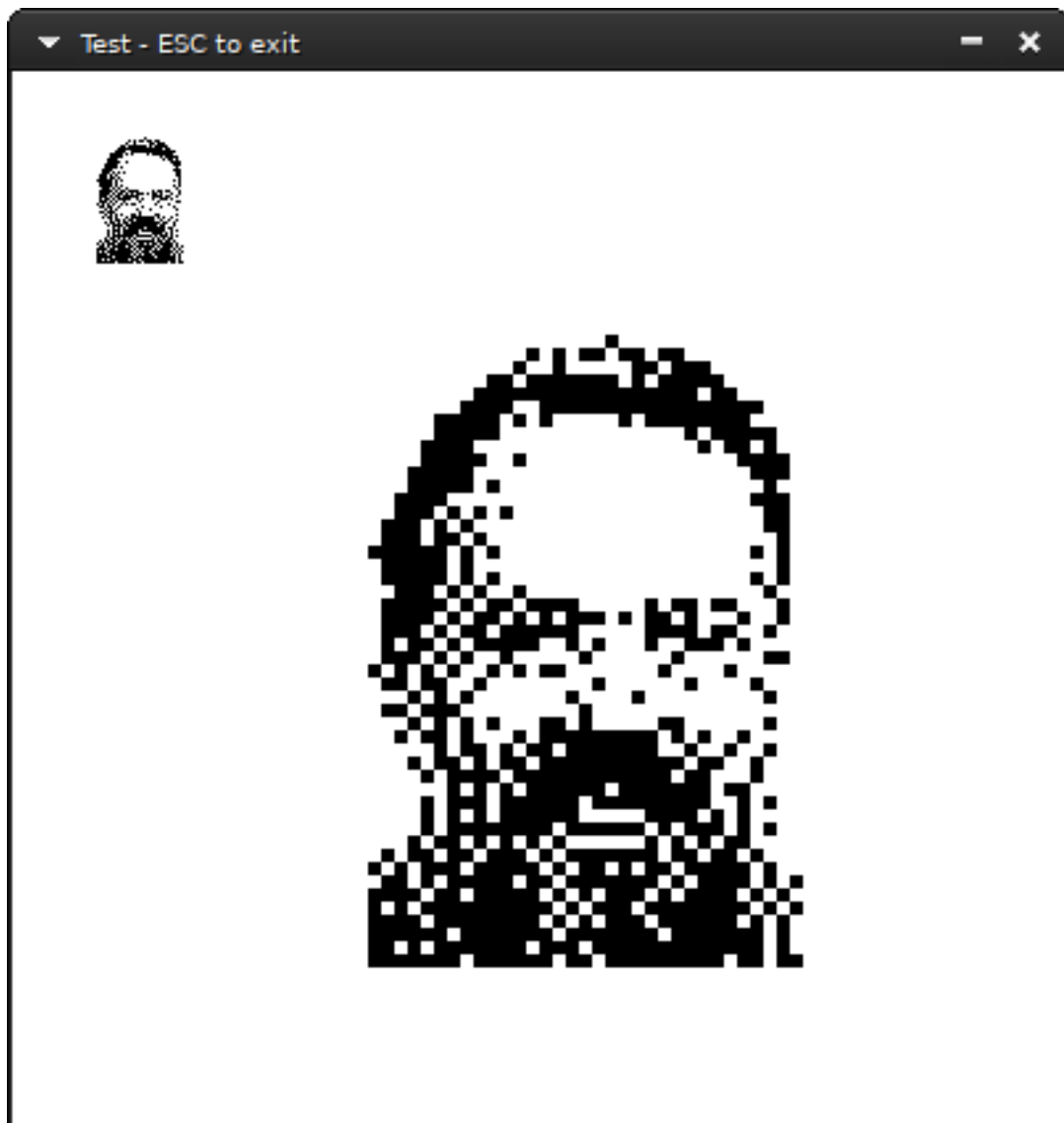
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## Chapter 24

# Magnification/Scaling



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```
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);
```

src/bin/scale.rs:



This code file is a PDF attachment

## 24.1 Smoothing enlarged bitmaps

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## 24.2 Stretching lines of bitmaps

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## Chapter 25

# Mirroring

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## Chapter 26

# Shearing

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## Chapter 27

# Projections

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transformations

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# **Part VIII**

## **Advanced**

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

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## Chapter 28

# Joining the ends of two wide line segments together



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## Chapter 29

## Composing monochrome bitmaps with separate alpha channel data

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## Chapter 30

## Orthogonal connection of two points

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## Chapter 31

# Join segments with round corners



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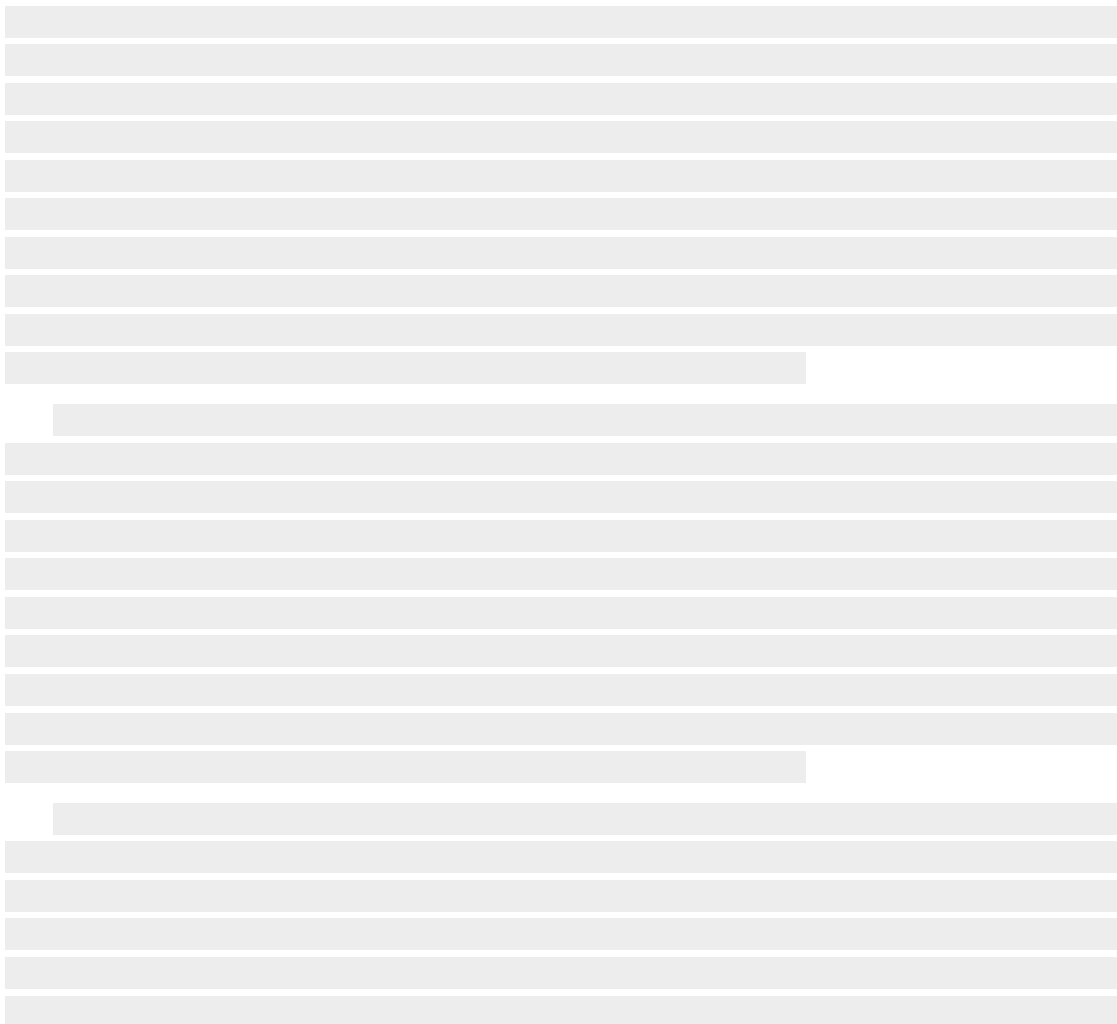
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## Chapter 32

# Faster line clipping



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## Chapter 33

# Space-filling Curves

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### 33.1 Hilbert curves

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# 33.2 Peano curves

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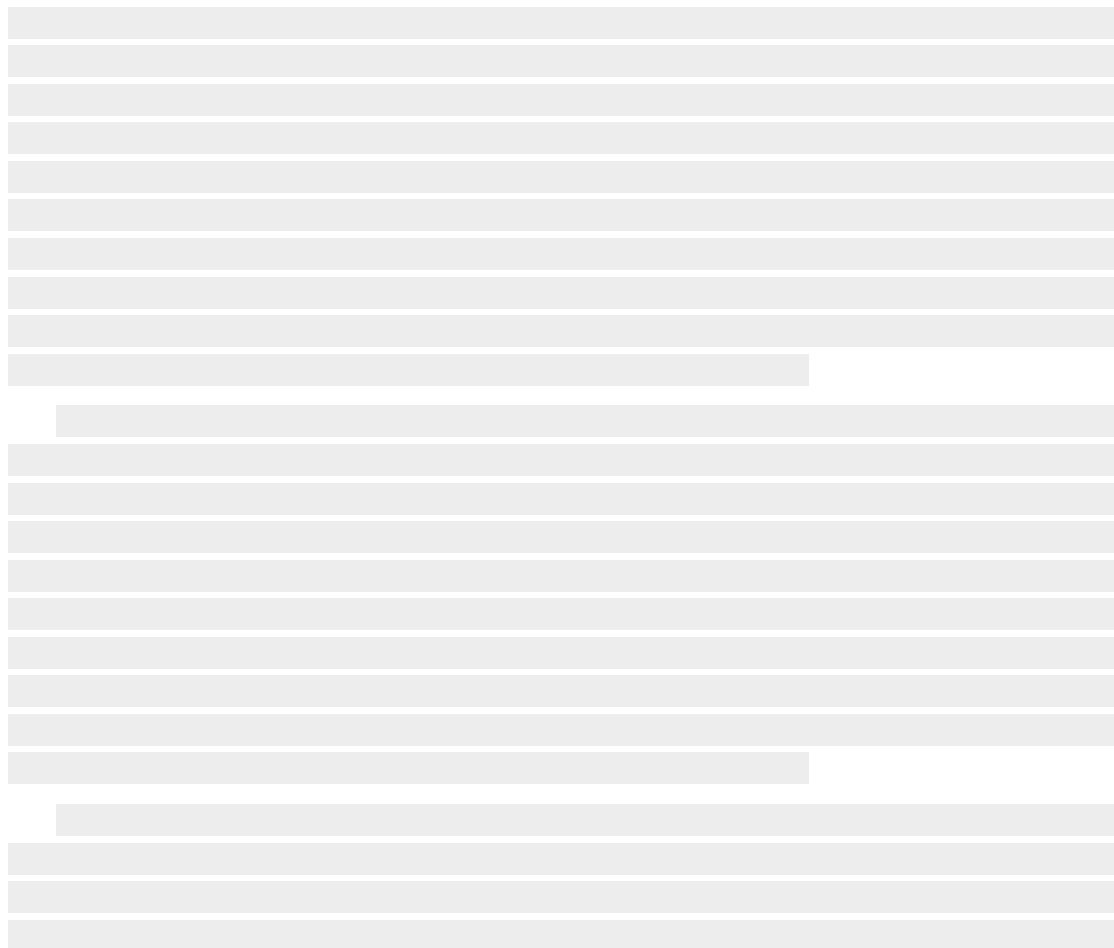
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### 33.3 Z-order curves



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# Index

centroid, 63, 75



## About this text

The text has been typeset in  $\text{\LaTeX}$  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.