

Drawing Lines with SystemVerilog

Prof. Stephen A. Edwards

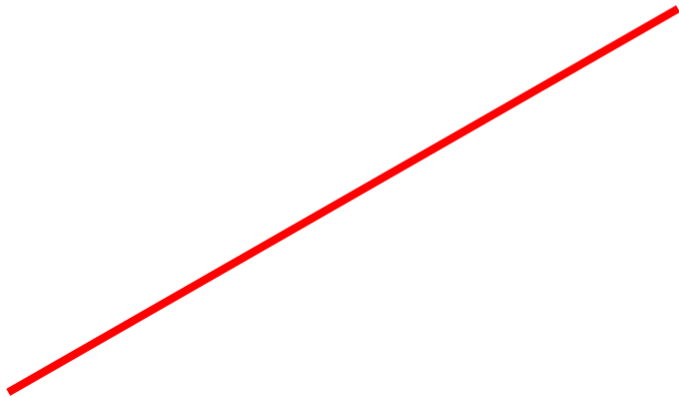
Columbia University

Spring 2022

Bresenham's Line Algorithm

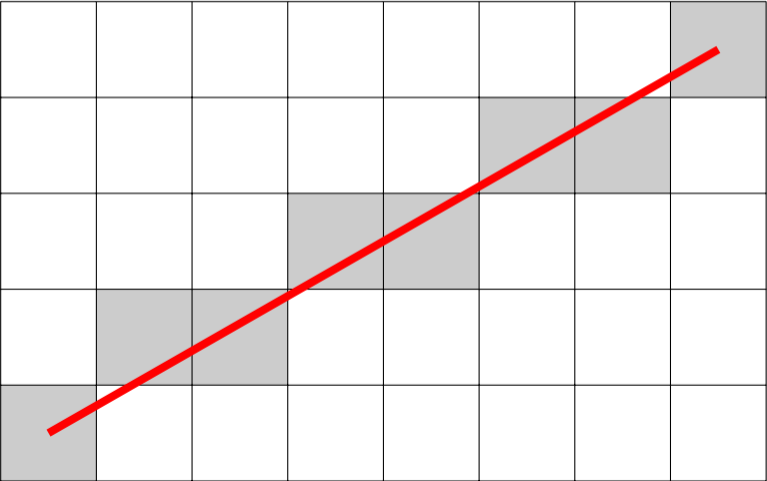
Bresenham's Line Algorithm

Objective: Draw a line...



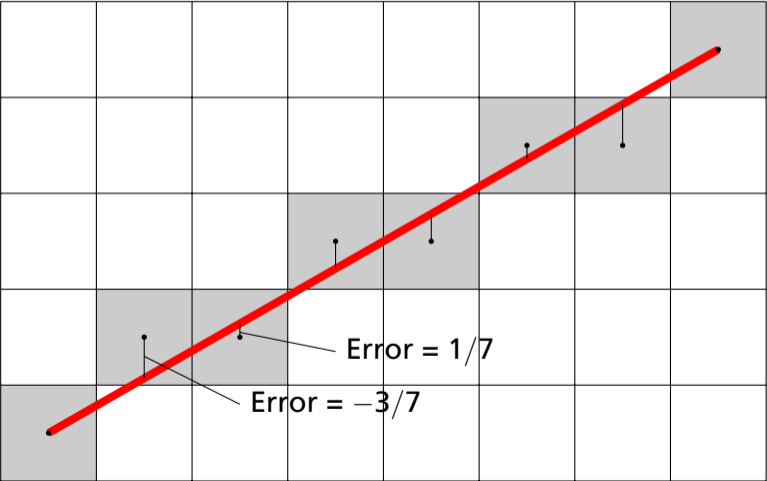
Bresenham's Line Algorithm

...with well-approximating pixels...



Bresenham's Line Algorithm

...by maintaining error information..



Approach

1. Understand the algorithm
I went to Wikipedia; doesn't everybody?
2. Code and test the algorithm in software
I used C and the SDL library for graphics
3. Define the interface for the hardware module
A communication protocol: consider the whole system
4. Schedule the operations
Draw a timing diagram!
In hardware, you must know in which cycle each thing happens.
5. Code in RTL
Always envision the hardware you are asking for
6. Test in simulation
Create a testbench: code that mimicks the environment (e.g., generates clocks, inputs).
7. Test on the FPGA
Simulating correctly is necessary but not sufficient.

The Pseudocode from Wikipedia

```
function line(x0, y0, x1, y1)
  dx := abs(x1-x0)
  dy := abs(y1-y0)
  if x0 < x1 then sx := 1 else sx := -1
  if y0 < y1 then sy := 1 else sy := -1
  err := dx-dy

  loop
    setPixel(x0,y0)
    if x0 = x1 and y0 = y1 exit loop
    e2 := 2*err
    if e2 > -dy then
      err := err - dy
      x0 := x0 + sx
    end if
    if e2 < dx then
      err := err + dx
      y0 := y0 + sy
    end if
  end loop
```


My C Code

```
void line(Uint16 x0, Uint16 y0, Uint16 x1, Uint16 y1)
{
    Sint16 dx, dy;    // Width and height of bounding box
    Uint16 x, y;      // Current point
    Sint16 err;       // Loop-carried value
    Sint16 e2;        // Temporary variable
    int right, down;  // Boolean

    dx = x1 - x0; right = dx > 0; if (!right) dx = -dx;
    dy = y1 - y0; down = dy > 0; if (down) dy = -dy;
    err = dx + dy; x = x0; y = y0;
    for (;;) {
        plot(x, y);
        if (x == x1 && y == y1) break; // Reached the end
        e2 = err << 1; // err * 2
        if (e2 > dy) { err += dy; if (right) x++; else x--;}
        if (e2 < dx) { err += dx; if (down) y++; else y--;}
    }
}
```

Module Interface

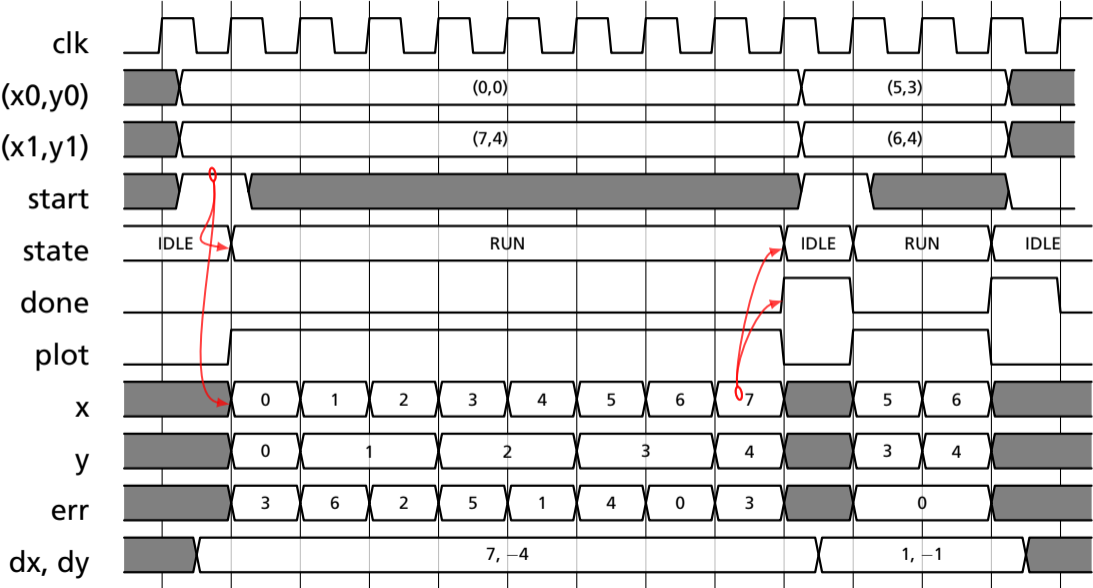
```
module bresenham(input logic      clk, reset,
                input logic      start,
                input logic [10:0] x0, y0, x1, y1,
                output logic      plot,
                output logic [10:0] x, y,
                output logic      done);
```

start indicates (x_0, y_0) and (x_1, y_1) are valid

plot indicates (x,y) is a point to plot

done indicates we are ready for the next *start*

Scheduling: Timing Diagram



RTL: The IDLE state

```
/* C code */
Sint16 dx;
Sint16 dy;
Uint16 x, y;
Sint16 err;
Sint16 e2;
int right;
int down;

dx = x1 - x0;
right = dx > 0;
if (!right) dx = -dx;
dy = y1 - y0;
down = dy > 0;
if (down) dy = -dy;

err = dx + dy;
x = x0;
y = y0;

for (;;) {
    plot(x, y);
```

```
logic signed [11:0] dx, dy, err, e2;
logic
    right, down;

typedef enum logic {IDLE, RUN} state_t;
state_t state;

always_ff @(posedge clk) begin
    done <= 0;
    plot <= 0;
    if (reset) state <= IDLE;
    else case (state)
        IDLE:
            if (start) begin
                dx = x1 - x0; // Blocking!
                right = dx >= 0;
                if (~right) dx = -dx;
                dy = y1 - y0;
                down = dy >= 0;
                if (down) dy = -dy;
                err = dx + dy;
                x <= x0;
                y <= y0;
                plot <= 1;
                state <= RUN;
            end
    endcase
end
```

RTL: The RUN state

```
/* C Code */
```

```
for (;;) {  
  plot(x, y);  
  if (x == x1 &&  
      y == y1)  
    break;  
  e2 = err << 1;  
  if (e2 > dy) {  
    err += dy;  
    if (right) x++;  
    else x--;  
  }  
  if (e2 < dx) {  
    err += dx;  
    if (down) y++;  
    else y--;  
  }  
}
```

```
RUN:
```

```
  if (x == x1 && y == y1) begin  
    done <= 1;  
    state <= IDLE;  
  end else begin  
    plot <= 1;  
    e2 = err << 1;  
    if (e2 > dy) begin  
      err += dy;  
      if (right) x <= x + 10'd 1;  
      else      x <= x - 10'd 1;  
    end  
    if (e2 < dx) begin  
      err += dx;  
      if (down) y <= y + 10'd 1;  
      else      y <= y - 10'd 1;  
    end  
  end  
  
  default:  
    state <= IDLE;  
  
endcase  
end
```

Datapath for dx , dy , *right*, and *down*

I: if (start)

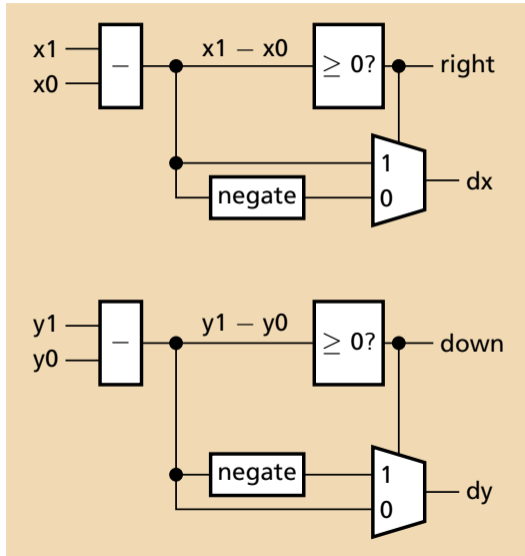
```
dx = x1 - x0;  
right = dx >= 0;  
if (~right) dx = -dx;  
dy = y1 - y0;  
down = dy >= 0;  
if (down) dy = -dy;  
err = dx + dy;  
x <= x0;  
y <= y0;  
plot <= 1;  
state <= RUN;
```

R: if (x == x1 && y == y1)

```
done <= 1;  
state <= IDLE;
```

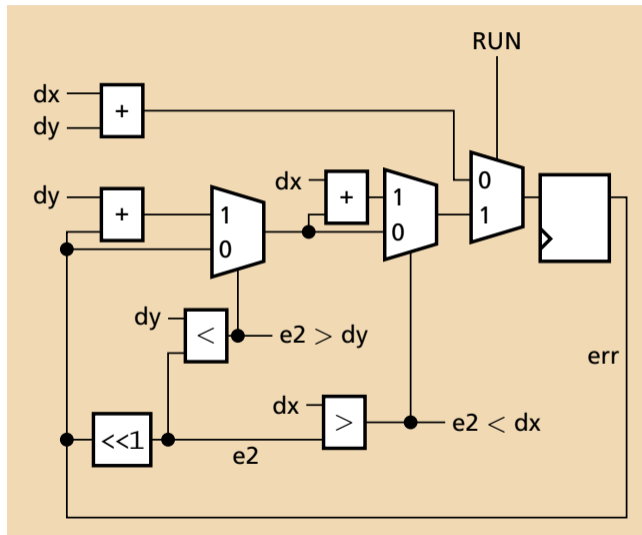
else

```
plot <= 1;  
e2 = err << 1;  
if (e2 > dy)  
    err += dy;  
    if (right) x <= x + 10'd 1;  
    else      x <= x - 10'd 1;  
if (e2 < dx)  
    err += dx;  
    if (down) y <= y + 10'd 1;  
    else     y <= y - 10'd 1;
```



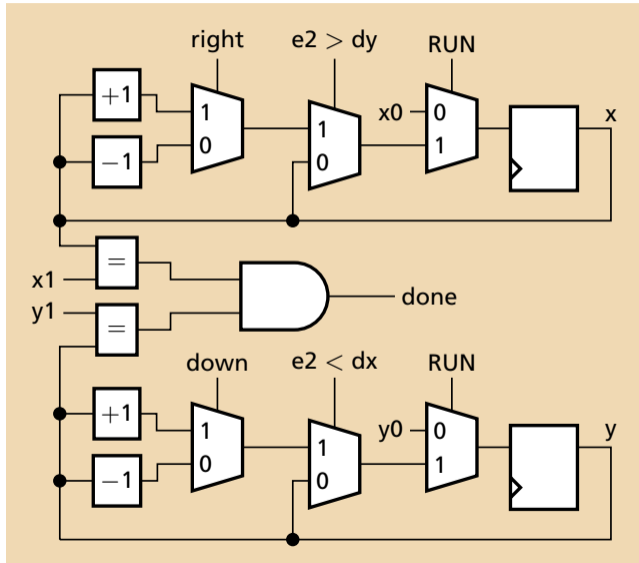
Datapath for err

```
I: if (start)
  dx = x1 - x0;
  right = dx >= 0;
  if (~right) dx = -dx;
  dy = y1 - y0;
  down = dy >= 0;
  if (down) dy = -dy;
  err = dx + dy;
  x <= x0;
  y <= y0;
  plot <= 1;
  state <= RUN;
R: if (x == x1 && y == y1)
  done <= 1;
  state <= IDLE;
else
  plot <= 1;
  e2 = err << 1;
  if (e2 > dy)
    err += dy;
  if (e2 < dx)
    err += dx;
  if (right) x <= x + 10'd 1;
  else x <= x - 10'd 1;
  if (down) y <= y + 10'd 1;
  else y <= y - 10'd 1;
```



Datapath for x and y

```
I: if (start)
  dx = x1 - x0;
  right = dx >= 0;
  if (~right) dx = -dx;
  dy = y1 - y0;
  down = dy >= 0;
  if (down) dy = -dy;
  err = dx + dy;
  x <= x0;
  y <= y0;
  plot <= 1;
  state <= RUN;
R: if (x == x1 && y == y1)
  done <= 1;
  state <= IDLE;
else
  plot <= 1;
  e2 = err << 1;
  if (e2 > dy)
    err += dy;
    if (right) x <= x + 10'd 1;
    else x <= x - 10'd 1;
  if (e2 < dx)
    err += dx;
    if (down) y <= y + 10'd 1;
    else y <= y - 10'd 1;
```



The Framebuffer: Interface and Constants

```
module VGA_framebuffer(  
  input logic      clk50, reset,  
  input logic [10:0] x, y, // Pixel coordinates  
  input logic      pixel_color, pixel_write,  
  
  output logic [7:0] VGA_R, VGA_G, VGA_B,  
  output logic      VGA_CLK, VGA_HS, VGA_VS, VGA_BLANK_n, VGA_SYNC_n);  
  
  parameter HACTIVE      = 11'd 1280,  
            HFRONT_PORCH = 11'd 32,  
            HSYNC        = 11'd 192,  
            HBACK_PORCH  = 11'd 96,  
            HTOTAL       =  
              HACTIVE + HFRONT_PORCH + HSYNC + HBACK_PORCH; //1600  
  
  parameter VACTIVE      = 10'd 480,  
            VFRONT_PORCH = 10'd 10,  
            VSYNC        = 10'd 2,  
            VBACK_PORCH  = 10'd 33,  
            VTOTAL       =  
              VACTIVE + VFRONT_PORCH + VSYNC + VBACK_PORCH; //525
```

The Framebuffer: Counters and Sync

```
// Horizontal counter
logic [10:0]                hcount;
logic                endOfLine;

always_ff @(posedge clk50 or posedge reset)
  if (reset)                hcount <= 0;
  else if (endOfLine) hcount <= 0;
  else                    hcount <= hcount + 11'd 1;

assign endOfLine = hcount == HTOTAL - 1;

// Vertical counter
logic [9:0]                vcount;
logic                endOfField;

always_ff @(posedge clk50 or posedge reset)
  if (reset)                vcount <= 0;
  else if (endOfLine)
    if (endOfField) vcount <= 0;
    else                vcount <= vcount + 10'd 1;

assign endOfField = vcount == VTOTAL - 1;

assign VGA_HS = !( (hcount[10:7] == 4'b1010) &
                   (hcount[6] | hcount[5]) );
assign VGA_VS = !( vcount[9:1] == (VACTIVE + VFRONT_PORCH) / 2);
```

The Framebuffer: Blanking, Memory, and RGB

```
assign VGA_SYNC_n = 1; // Sync on R, G, and B. Unused for VGA.

logic        blank;
assign blank = ( hcount[10] & (hcount[9] | hcount[8]) ) | // 1280
               ( vcount[9] | (vcount[8:5] == 4'b1111) ); // 480

logic        framebuffer [307199:0]; // 640 * 480
logic [18:0] read_address, write_address;

assign write_address = x + (y << 9) + (y << 7) ; // x + y * 640
assign read_address =
    (hcount >> 1) + (vcount << 9) + (vcount << 7);

logic        pixel_read;
always_ff @(posedge clk50) begin
    if (pixel_write) framebuffer[write_address] <= pixel_color;
    if (hcount[0]) begin
        pixel_read <= framebuffer[read_address];
        VGA_BLANK_n <= ~blank; // Sync blank with read pixel data
    end
end

assign VGA_CLK = hcount[0]; // 25 MHz clock
assign {VGA_R, VGA_G, VGA_B} = pixel_read ? 24'hFF_FF_FF : 24'h0;
endmodule
```

The "Hallway" Line Generator

```
module hallway(input logic      clk, reset,
               input logic      VGA_VS,

               input logic      done,

               output logic [10:0] x0, y0, x1, y1,
               output logic      start, pixel_color);

// ...

// Typical state:

S_TOP:
  if (done) begin
    start <= 1;
    if (x0 < 620)
      x0 <= x0 + 10'd 10;
    else begin
      state <= S_RIGHT;
      x0 <= 639;
      y0 <= 0;
    end
  end
end
```

Connecting the Pieces

```
// SoCKit_Top.sv
```

```
logic [10:0]      x, y, x0,y0,x1,y1;  
logic            pixel_color;  
logic            pixel_write;  
logic            done, start;
```

```
VGA_framebuffer fb(.clk50(OSC_50_B3B),  
                  .reset(~RESET_n),  
                  .*);
```

```
bresenham liner(.clk(OSC_50_B3B),  
               .reset(~RESET_n),  
               .plot(pixel_write),  
               .*);
```

```
hallway hall(.clk(OSC_50_B3B),  
             .reset(~RESET_n),  
             .* );
```

Connect the bresenham
reset port to
an inverted *RESET_n*

Connect the other
bresenham ports to wires
with the same name
e.g., *.x(x), .y(y),...*