Drawing Lines with SystemVerilog

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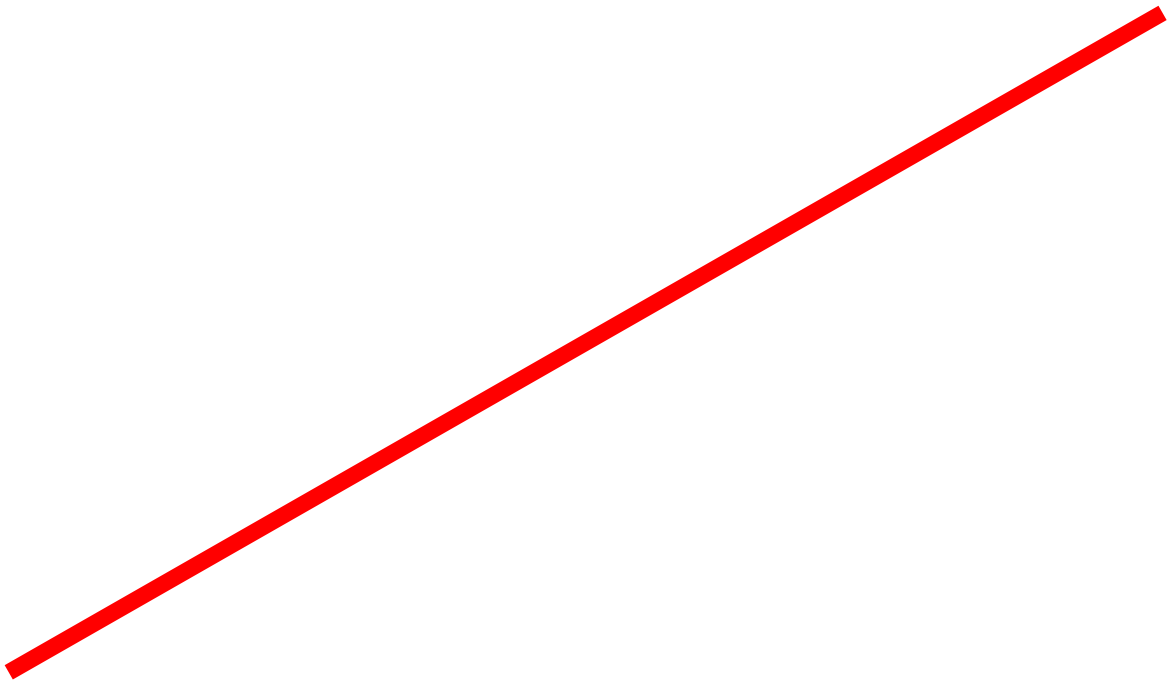
Bresenham's Line Algorithm

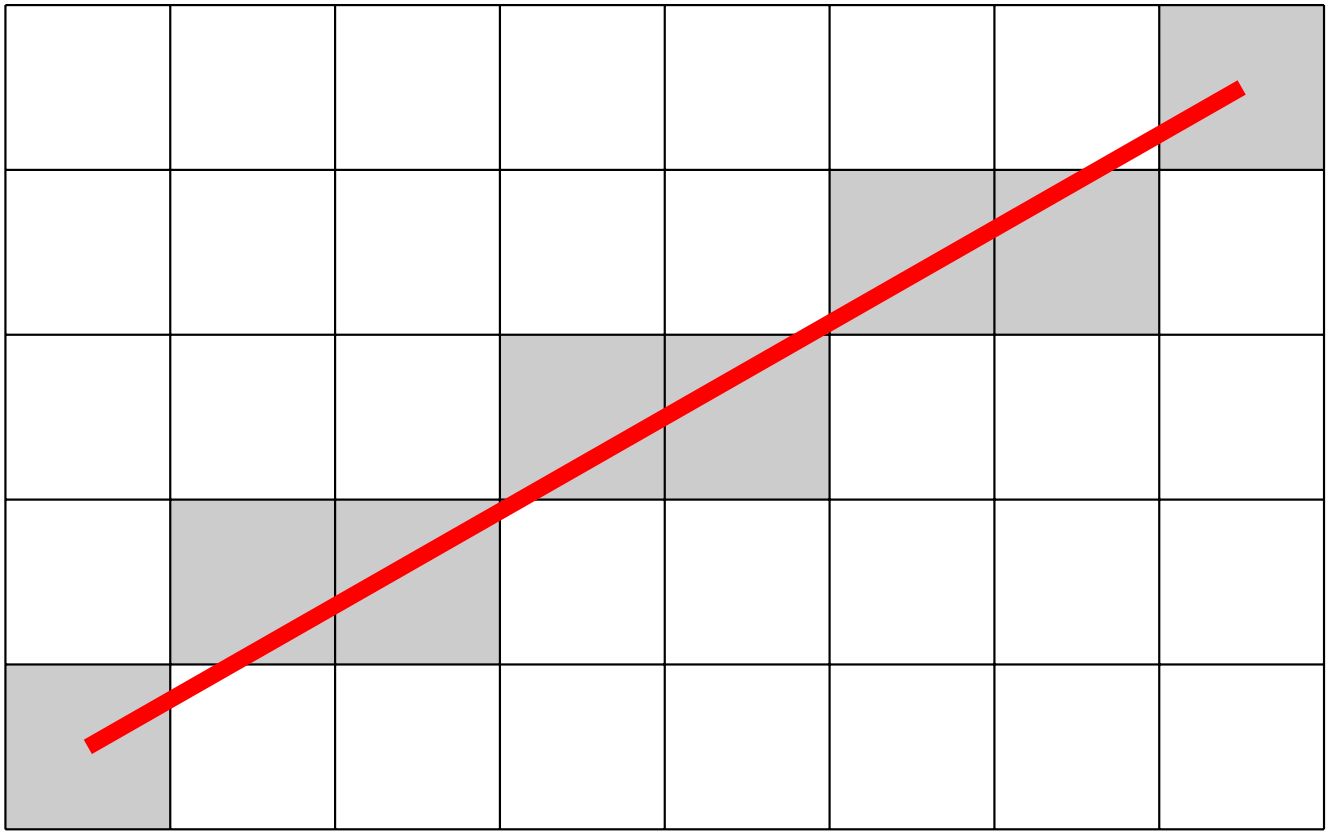
Bresenham's Line Algorithm

Objective:Draw a line...



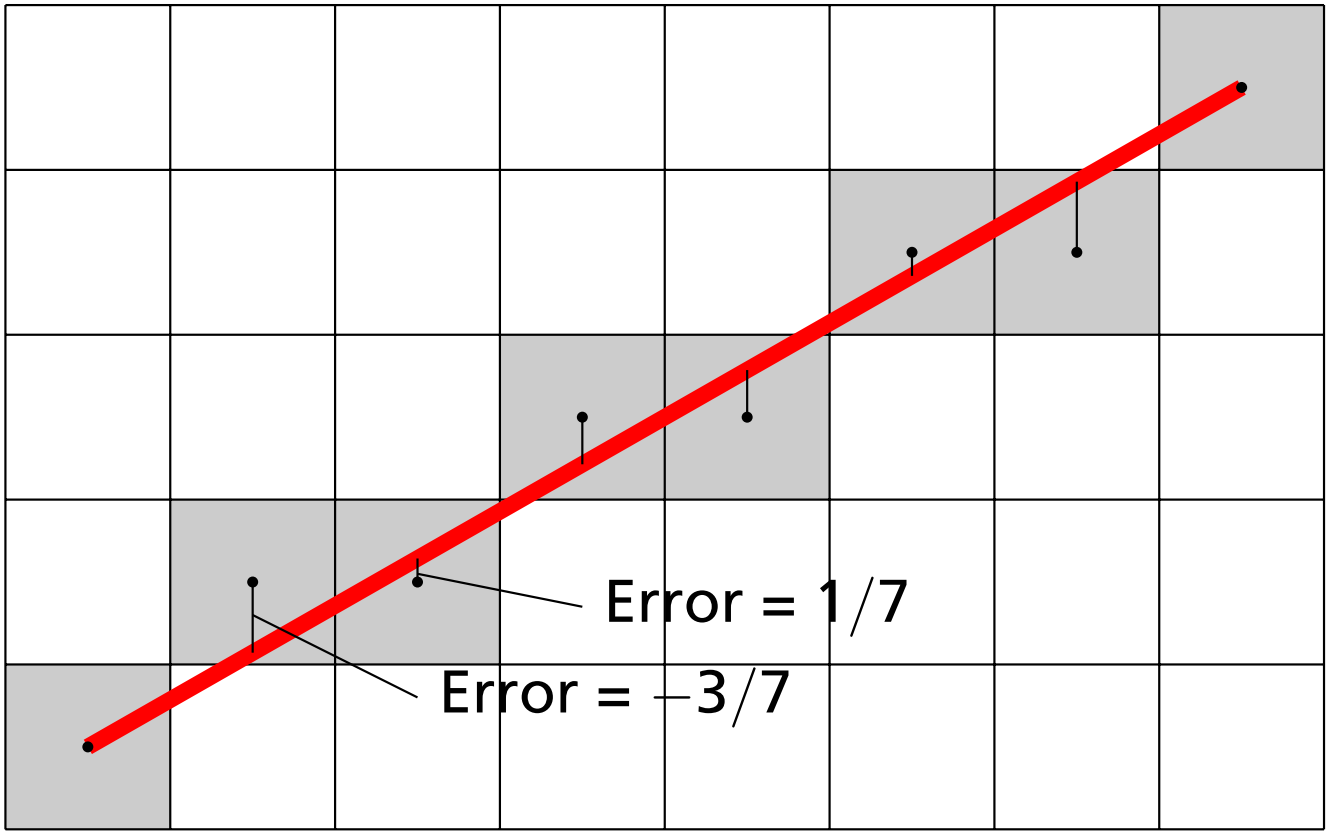
Bresenham's Line Algorithm

...with well-approximating pixels...



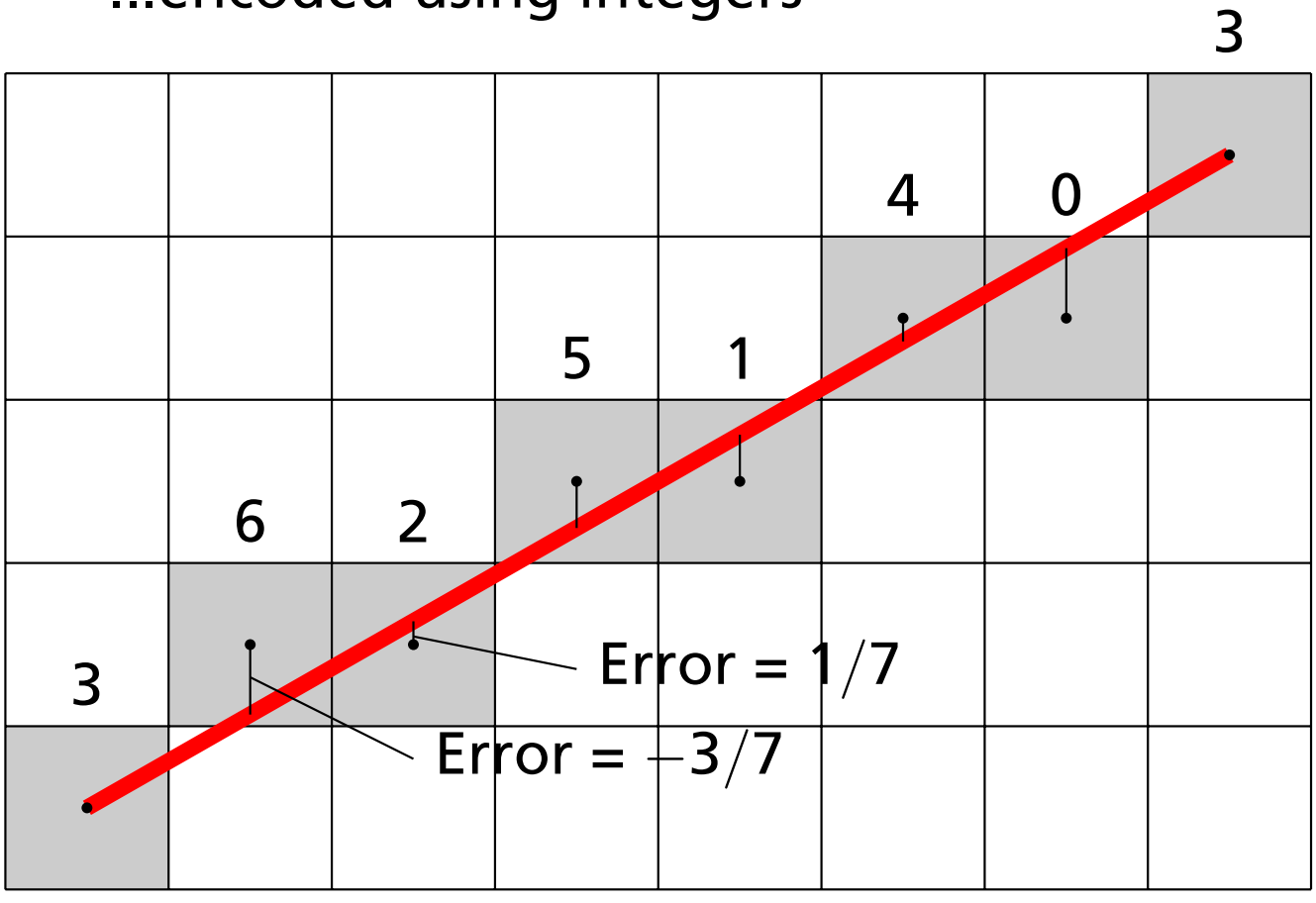
Bresenham's Line Algorithm

...by maintaining error information..



Bresenham's Line Algorithm

...encoded using integers



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

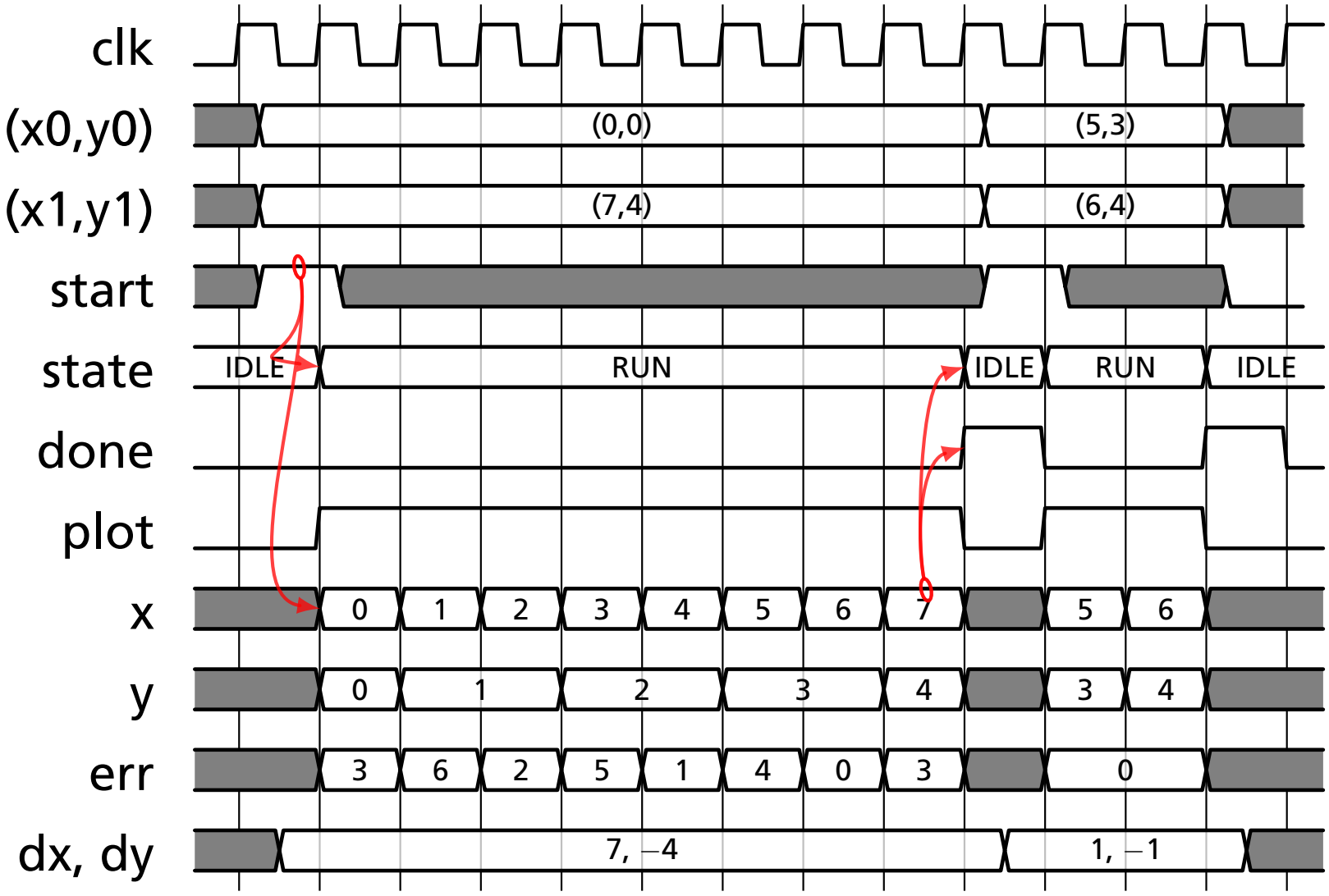
```
module bresenham(input logic         clk, reset,

                 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 (*x0*, *y0*) and (*x1*, *y1*) 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
```

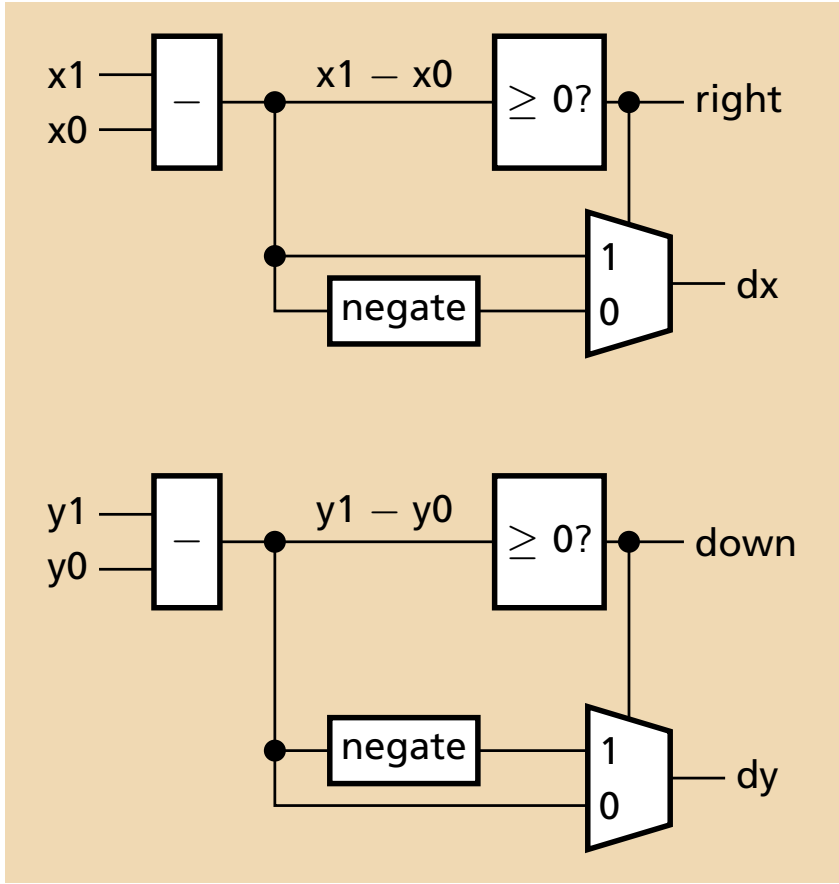
RTL: The RUN state

```
/* 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
```

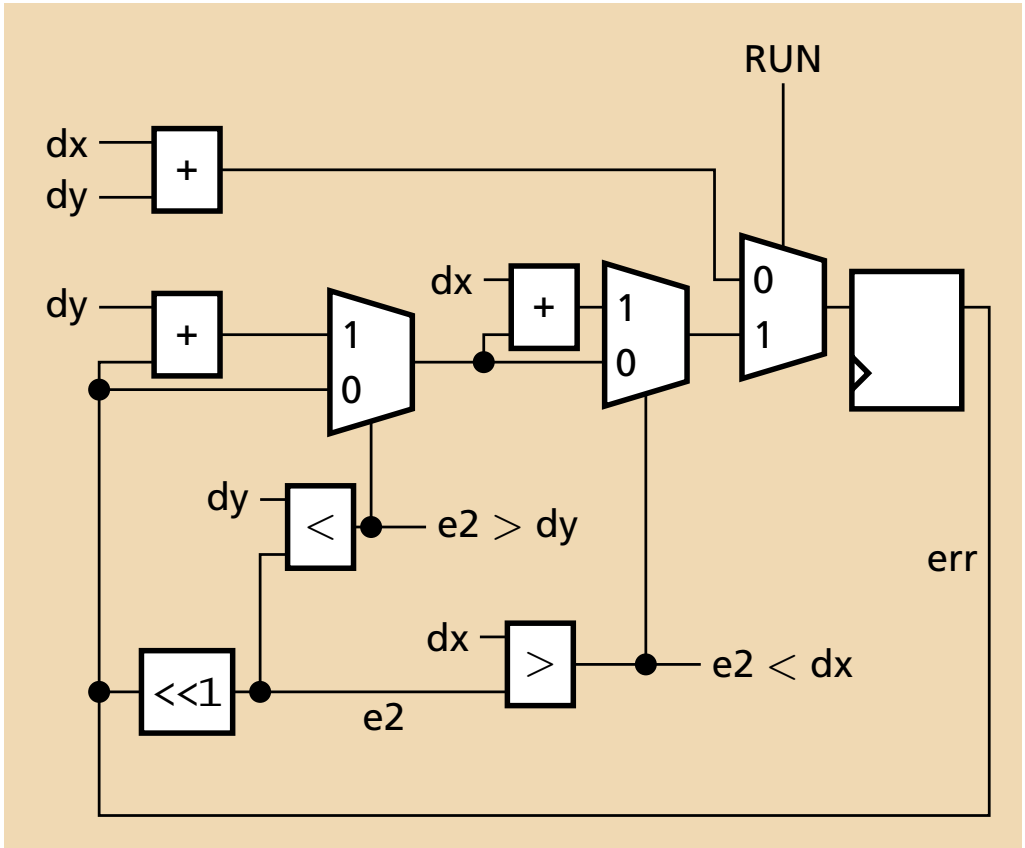
Datapath for *dx*, *dy*, *right*, and *down*

```
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;
```



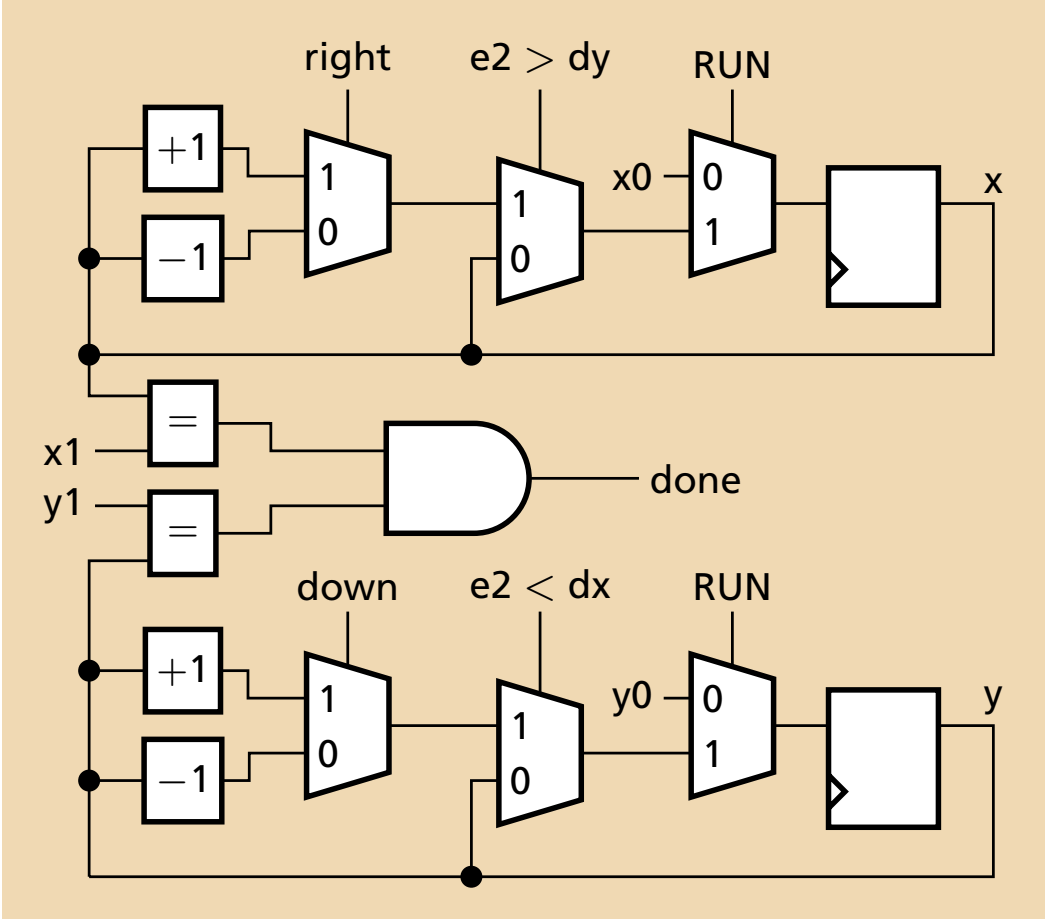
Datapath for *err*

```
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 (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 *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
```

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),...