Retrocomputing with Clash

Haskell for FPGA Hardware Design

GERGŐ ÉRDI

https://unsafePerform.IO/retroclash/

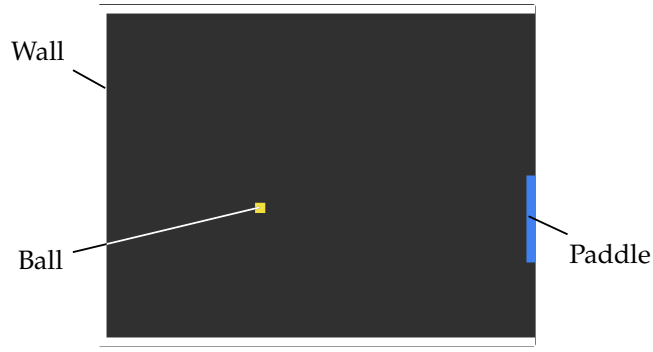
9 Project: Pong

In this chapter, we answer the call of the bouncing ball example circuit from the previous chapter, and build our own version of Pong, one of the earliest video games.

The original Pong didn't run on a computer: instead, its game logic and its video output was all implemented directly as a circuit of discrete components. Our version will also be computer-less; however, rather than building a rat's nest of connected registers, we will apply the same principled design as we did in the Calculator project.

9.1 What is Pong?

Pong is a very minimalistic video game simulation of tennis. Players control paddles on the sides of the screen, by moving them vertically. A ball is bouncing between the paddles and the top and bottom edges of the screen. The aim of the player is to not let the ball go out of bounds on their side. In the original two-player version, there are two paddles, one for each player. Here, we will build a solitaire version first, and leave the two-player version as an exercise. Basically, our game is going to be the squash equivalent to Pong's tennis.



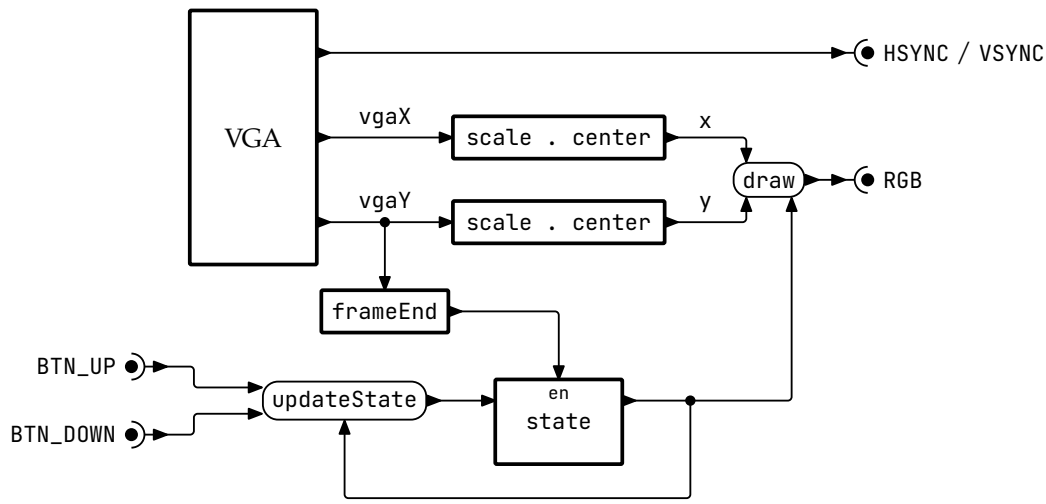
From the outside point of view, Pong is a circuit which outputs a video signal

and connects to inputs for paddle control. We will use two pushbuttons for moving the paddle up or down, and generate VGA in 640×480@60 mode for the video output. Just for the fun of it, and to give it that nice chunky retro look, the game itself will only use 256×200 resolution, which we will scale up by two and centered it on the screen.

9.2 Top-level design

Internally, we will follow the same design as the bouncing ball toy: a register holding the state, a state transition function consuming input, and a drawing function that takes the current state, and turns it into output.

Putting it all together, our design will be as follows:



This is the same design as the bouncing ball one, with an added coordinate transformation to end up with a drawing area of 256×200, and input from the outside world in the form of the two pushbuttons controlling the paddles.

With all this groundwork laid, it is time to work out the missing details:

- `data Inputs`, a record that holds all user inputs
- `data St`, the game state
- `updateState :: Inputs -> St -> St`, the state transition function
- `draw :: St -> Index 256 -> Index 200 -> Color`, the drawing function

Once these are filled in, our `topEntity` will mostly match that of the bouncing ball circuit:

```
data Inputs = MkInputs
    { paddleUp :: Bool
    , paddleDown :: Bool
    }

type ScreenWidth = 256
type ScreenHeight = 200

topEntity
    :: "CLK_25MHZ" ::: Clock Dom25
    -> "RESET"     ::: Reset Dom25
    -> "BTN_UP"    ::: Signal Dom25 (Active High)
    -> "BTN_DOWN"  ::: Signal Dom25 (Active High)
    -> "VGA"       ::: VGAOut Dom25 8 8 8
topEntity = withEnableGen board
  where
    board (fmap fromActive -> up) (fmap fromActive -> down) = vgaOut
    vgaSync rgb
      where
        VGADriver{..} = vgaDriver vga640x480at60
        frameEnd = isFalling False (isJust <$> vgaY)

        params = defaultParams
        inputs = MkInputs <$> up <*> down

        st = regEn initState frameEnd $
            updateState params <$> inputs <*> st

        rgb = fmap (maybe (0, 0, 0) bitCoerce) $
            liftA2 <$> (draw params <$> st) <*> x <*> y
          where
            (x, _) = scale (SNat @2) . center $ vgaX
            (y, _) = scale (SNat @2) . center $ vgaY
```

Accordingly, the SDL-based simulator's `main` function also remains mostly the same. We increase the scaling factor to 4, since the virtual screen we are simulating now is only 256×200 pixels – remember, the transformation to 640×480 takes place only in `topEntity`, as a measure to convert to a standard video format that real-world screens can understand. This conversion is morally no different from converting the `Active High` pushbutton values to a semantic `Bool`, so we put it outside `draw`.

```
main :: IO ()
main =
    flip evalStateT initState $
    withMainWindow videoParams $ \events keyDown -> do
        guard $ not $ keyDown ScancodeEscape

        let params = defaultParams
        modify $ updateState params $ MkInputs
            { paddleUp = keyDown ScancodeUp
            , paddleDown = keyDown ScancodeDown
            }
        gets $ rasterizePattern . draw params
  where
    videoParams = MkVideoParams
        { windowTitle = "Pong"
        , screenScale = 4
        , screenRefreshRate = 60
        }
```

To recap, the signatures of the remaining parts to implement are:

```
data St

updateState :: Params -> Inputs -> St -> St
draw :: Params -> St -> Index ScreenWidth -> Index ScreenHeight -> Color
```

9.3 What is our state?

Compared to just a ball bouncing around in the emptiness of a video screen, a game of Pong is similar in some ways and different in others:

- There is a ball bouncing around in both cases. Our `State` will need to hold the ball's position and speed just like before.
- Pong has another moving part: the paddle. Since it can only be moved vertically, only its Y position needs to be stored.
- We want to draw the ball as before, but of course we also want to draw the paddle (at the right position). To emphasize to the player that it is their responsibility to hit the ball back from the right-hand edge, we will also draw walls around the other three edges of the screen.
- Pong is interactive: the player can move the paddle up or down. We take care of this by adding an extra `Inputs` parameter to `updateState`.

- There is also some complicated interaction between the ball and the paddle. At the minimum, the ball bounces off the paddle when it hits it; but that alone makes for a very boring variant of Pong. We will spice it up a notch by allowing the paddle to nudge the ball vertically, if the paddle itself is moving vertically at the moment of contact.
- Pong is a game with a goal: to avoid the ball leaving the playfield by flying off to the right. We should give some kind of indication of failure when that happens: we will flash the background color in red for one frame.

Based on this analysis, it is clear that `St` should extend the horizontal and vertical speed-and-position of the ball with a vertical paddle position, and a flag denoting if we should draw the background in the given frame in red. `updateFlag` will always clear that flag (unless, of course, the ball is just now leaving the game area); this ensures that it will flash for one frame only.

```
type Coord = Signed 10

data St = MkSt
    { _ballH, _ballV :: (Coord, Coord)
    , _paddleY :: Coord
    , _gameOver :: Bool
    }
    deriving (Show, Generic, NFDataX)
makeLenses ''St

initState :: St
initState = MkSt
    { _ballH = (10, 2)
    , _ballV = (100, 3)
    , _paddleY = 100
    , _gameOver = False
    }
```

The `Params` datatype likewise extends the ball size with new fields for the width of the walls and the size of the paddle. We also need to know how much to move the paddle on each frame if the user is holding one of the input buttons, and how much nudge should be applied to the ball when hitting it with a moving paddle.

```
data Params = MkParams
    { wallSize, ballSize :: Coord
    , paddleHeight, paddleWidth :: Coord
    , paddleSpeed, nudgeSpeed :: Coord
    }
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```

```
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defaultParams :: Params
defaultParams = MkParams
    { wallSize = 5
    , ballSize = 5
    , paddleHeight = 50
    , paddleWidth = 5
    , paddleSpeed = 3
    , nudgeSpeed = 3
    }
```

9.3.1 `updateState`

If we know what is in our state, we also know how to update it: we just update every component of it, using appropriate helper functions. The devil will be in the details of them, but we can keep this top-level `updateState` simple:

```
updateState :: Params -> Inputs -> St -> St
updateState params inp = execState $ do
    updateBall params inp
    updatePaddle params inp
    checkBounds params
```

Updating the ball is very similar to our previous code: we update its horizontal and vertical position and speed separately. Vertically, there is no extra complication; but horizontally, we need to include the paddle as a reflector only if the ball is (vertically) where the paddle is. Moreover, to implement nudging the ball on a hit with the paddle, we need to detect that collision; so we will extend `reflect` slightly to return an additional `Bool` denoting collisions.

```
reflect
    :: (Num a, Num a', Ord a, Ord a')
    => (a, a')
    -> (a, a')
    -> (Bool, (a, a'))
reflect (p, n) (x, dx)
    | sameDirection n dist = (True, (p + dist, negate dx))
    | otherwise = (False, (x, dx))
  where
    sameDirection u v = compare 0 u == compare 0 v
    dist = p - x
```

We will use `reflect` and `move` in our `State St` monad, so let's use a shorthand for their lifted versions:

```
moveM :: (Num a) => State (a, a) ()
moveM = modify move

reflectM :: (Num a, Num a', Ord a, Ord a') => (a, a') -> State (a, a')
    Bool
reflectM = state . reflect
```

This gives us everything to implement `updateBall`:

- `updateVert` simply moves the ball and checks for reflections from the top and bottom walls:

```
updateVert :: Params -> State St ()
updateVert MkParams{..} = void $ do
    zoom ballV $ do
      moveM
      reflectM (wallSize, 1)
      reflectM (screenHeight - wallSize - ballSize, -1)
```

- `updateHoriz` looks at the vertical position to see we are at the height of the paddle, and decides based on that whether to include a second reflector on the right-hand size.

```
updateHoriz :: Params -> State St Bool
updateHoriz MkParams{..} = do
    atPaddle <- do
        paddleY <- use paddleY
        (y, _) <- use ballV
        return $ y `between` (paddleY - ballSize, paddleY +
    paddleHeight)
    zoom ballH $ do
        moveM
        reflectM (wallSize, 1)
        if not atPaddle then return False
          else reflectM (screenWidth - paddleWidth - ballSize, -1)
```

- `updateBall` itself runs `updateVert` and `updateHoriz`, and changes the vertical ball speed if `updateHoriz` returns `True`, i.e. if there was a collision with the paddle:

```
updateBall :: Params -> Inputs -> State St ()
updateBall params@MkParams{..} MkInputs{..} = do
    updateVert params
    hitPaddle <- updateHoriz params
    when hitPaddle $ ballV._2 += nudge
  where
    nudge | paddleDown = nudgeSpeed
          | paddleUp = negate nudgeSpeed
          | otherwise = 0
```

Compared to the complicated logic of checking for bounces and paddle hits, updating the paddle's state is much simpler: we increase or decrease `paddleY` by `paddleSpeed` depending on which input buttons are held in the given frame, and then ensure it stays in the playfield:

```
updatePaddle :: Params -> Inputs -> State St ()
updatePaddle MkParams{..} MkInputs{..} = do
    when paddleUp $ paddleY -= paddleSpeed
    when paddleDown $ paddleY += paddleSpeed
    paddleY %= clamp (wallSize, screenHeight - (wallSize + paddleHeight))

clamp :: (Ord a) => (a, a) -> a -> a
clamp (lo, hi) = max lo . min hi
```

To detect the ball going out of bounds, we simply check if its X coordinate is larger than the screen width. This way, even after the ball passes the point of no return at the edge of the paddle, we will keep drawing it until it fully leaves the screen – increasing the player's frustration just a bit more.

It is here that we set the `gameOver` field of the state. As mentioned earlier, this field is set to `True` only for the duration of the single frame when the ball actually flies out of bounds – in the next frame, the ball is already reset into the middle of the playfield (keeping its current speed and Y coordinate).

```
checkBounds :: Params -> State St ()
checkBounds MkParams{..} = do
    outOfBounds <- zoom ballH $ gets $ \(x, _) -> x > screenWidth
    gameOver .= outOfBounds
    when outOfBounds resetBall
  where
    resetBall = ballH._1 .= half screenWidth
```

9.4 Drawing

The main structure of `draw` is very similar to the bouncing ball example: we just have more shapes to check against the current raster beam position.

```
draw :: Params -> St -> Index ScreenWidth -> Index ScreenHeight -> Color
draw MkParams{..} MkSt{..} ix iy
    | isWall    = white
    | isPaddle  = blue
    | isBall    = yellow
    | otherwise = if _gameOver then red else gray
  where
    x = fromIntegral ix
    y = fromIntegral iy

    rect (x0, y0) (w, h) =
        x `between` (x0, x0 + w) &&
        y `between` (y0, y0 + h)

    -- Continued below
```

The definitions of the individual shapes are all straightforward: the paddle and the ball are rectangles, and each wall is an even simpler comparison.

```
    isWall = or
        [ x < wallSize
        , y < wallSize
        , y >= screenHeight - wallSize
        ]

    paddleStart = screenWidth - paddleWidth
    isPaddle = rect (paddleStart, _paddleY) (paddleWidth, paddleHeight)

    (ballX, _) = _ballH
    (ballY, _) = _ballV
    isBall = rect (ballX, ballY) (ballSize, ballSize)
```

For completeness's sake, here are some RGB values for these colors that hopefully won't hurt the player's eyes too much:

```
white, blue, yellow, red, gray :: Color
white  = (0xff, 0xff, 0xff)
blue   = (0x40, 0x80, 0xf0)
yellow = (0xf0, 0xe0, 0x40)
red    = (0x80, 0x00, 0x00)
gray   = (0x30, 0x30, 0x30)
```

By plugging these definitions of `St`, `updateState`, and `draw` into our `topEntity` and `main`, we finish our implementation of (solitaire) Pong, including an interactive SDL simulation.

Exercises:

- On each successful hit, flash the part of the physical screen that is outside the playing area of the virtual screen.
- Increase difficulty as the game goes on by decreasing the paddle size on every k^{th} successful hit, up to a reasonable minimum paddle size.
- Draw the ball as a more round shape.
- Keep score. Drawing numerals would be quite hard with what we have so far, but we could e.g. draw a progress bar counting up to 10 misses.
- Two-player mode. This should be quite self-explanatory: hook up two more buttons to move a second, left-hand side paddle up and down. The score could be displayed as a tug-of-war progress bar.
- A fun variant of two-player Pong is to give a third "boost" button to both players, and scale up the ball's speed by two if exactly one of the players is holding their boost button.

9.5 Summary

- Starting with the implementation of the bouncing ball circuit, the only structural change is adding an **input** signal.
- The rest of the changes are in the definition of the **state datatype** and its **transition function**. These are all "normal", pure Haskell parts that we just happen to use in the context of a Clash circuit.