Executable, Synthesizable, Human Readable: Pick Three

Pong on an FPGA with Clash

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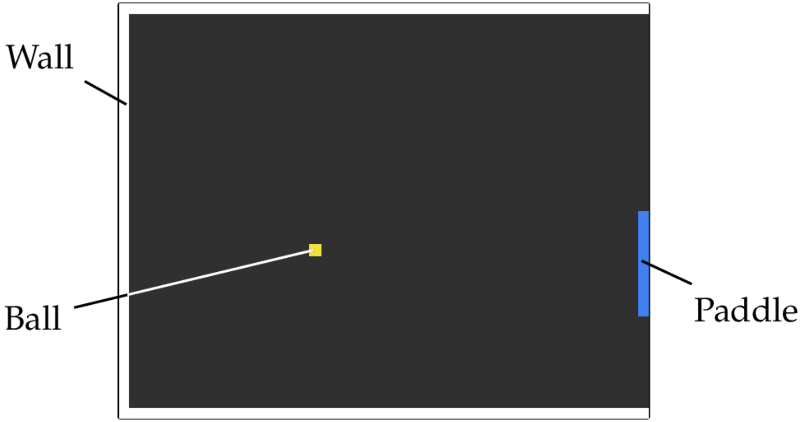
https://unsafePerform.IO/

Haskell Love, 10th September 2021.

(Solitaire) Pong



1. Software implementation

Game state

- `data St`
- `initState :: St`
- `updateState :: Inputs -> St -> St`

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```
type Coord = Signed 10

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

Game state

- `data St`
- `initState :: St`
- `updateState :: Inputs -> St -> St`

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

Game state

- `data St`
- `initState :: St`
- `updateState :: Inputs -> St -> St`

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

updateState inp = execState $ do
    updateBall          -- Bounce on walls and paddle
    updatePaddle inp    -- Move paddle based on user input
    checkBounds         -- Ball out of bounds?
```

updateBall details

Decomposed in vertical (walls only) and horizontal (walls or paddle) direction:

```
updateBall :: State St ()
updateBall = do
    updateVert
    updateHoriz
```

updateBall details

Decomposed in vertical (walls only) and horizontal (walls or paddle) direction:

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

Drawing

```
type ScreenWidth = 256
type ScreenHeight = 200

type X = Index ScreenWidth
type Y = Index ScreenHeight

type Color = (Unsigned 8, Unsigned 8, Unsigned 8)

draw :: St -> X -> Y -> Color
draw MkSt{..} x y
    | isWall    = white
    | isPaddle  = blue
    | isBall    = yellow
    | otherwise = if _gameOver then red else gray
```

High-level simulation

Everything we have so far is normal (and nice!) Haskell code

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

        modify $ updateState $ MkInputs
            { paddleUp   = keyDown ScancodeUp
            , paddleDown = keyDown ScancodeDown
            }
        gets $ rasterizePattern . draw
```

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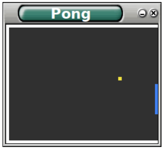

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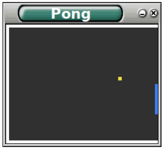

```
videoParams = MkVideoParams
    { windowTitle = "Pong"
    , screenScale = 1
    , screenRefreshRate = 60
    , reportFPS = True
    }
```

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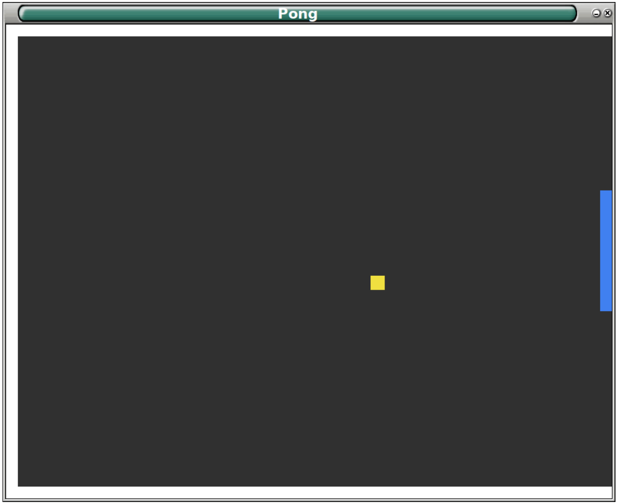

2. Hardware implementation

Field-Programmable Gate Arrays

FPGA is a collection of logic gates and registers where the connections are electronically configurable

A chip fab on your desk

Physical connectors with appropriate electric properties to peripherals

Wide range of performance, price and built-in IO

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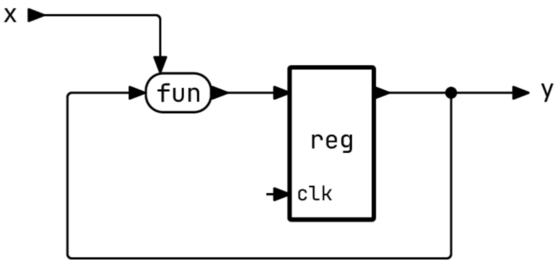
Horrible toolchains taking Verilog or VHDL input

Clash: Haskell to Hardware (FPGAs, ASICs)

- `Signal :: Domain -> Type -> Type`
- `instance Applicative (Signal dom)`
- `register :: a -> Signal dom a -> Signal dom a`

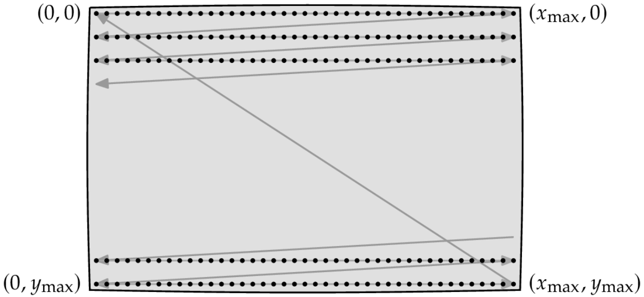
Register transfer-level model:

```
y = register y0 (fun <$> x <*> y)
```



Video output via VGA

- VGA: old analog video standard
- Sweet spot of theoretical simplicity and widespread support both by displays and FPGA development boards
- Three separate color channels
- Separate horizontal and vertical sync lines



Reusable VGA signal generator

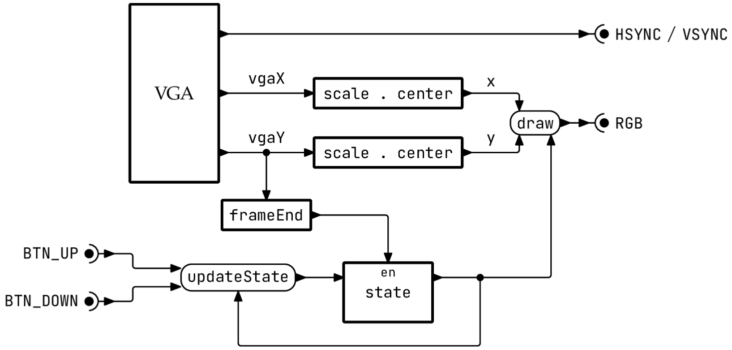
Type-level tracking of resolution & pixel clock:

```
data VGADriver dom w h = VGADriver
    { vgaSync :: VGASync dom
    , vgaX    :: Signal dom (Maybe (Index w))
    , vgaY    :: Signal dom (Maybe (Index h))
    }

vgaDriver
    :: (HiddenClockResetEnable dom, KnownNat w, KnownNat h)
    => (DomainPeriod dom ~ ps)
    => VGATimings ps w h
    -> VGADriver dom w h

vga640x480at60 :: VGATimings (HzToPeriod 25_175_000) 640 480
```

Hardware design for Pong



- Typed coordinate transformations: `center`, `scale`

```
vgaX :: _ (Maybe (Index 640))
scale (SNat @2) . center $ vgaX  :: _ (Maybe (Index 256))
```

Pong circuit in Clash

```
-- Template Haskell macro to generate pixel clock
createDomain vSystem
  { vName="Dom25"
  , vPeriod = hzToPeriod 25_175_000
  }

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
```

Pong circuit in Clash

```
board (fmap fromActive -> up) (fmap fromActive -> down) =
    vgaOut vgaSync rgb
  where
    VGADriver{..} = vgaDriver vga640x480at60
    frameEnd = isFalling False (isJust <$> vgaY)

    inputs = MkInputs <$> up <*> down

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

    rgb = withBorder <$> pure (0,0,0) <*>
        (draw <$> st) <*> x <*> y
      where
        (x, _) = scale (SNat @2) . center $ vgaX
        (y, _) = scale (SNat @2) . center $ vgaY
```

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- *Woke*: interactive simulation

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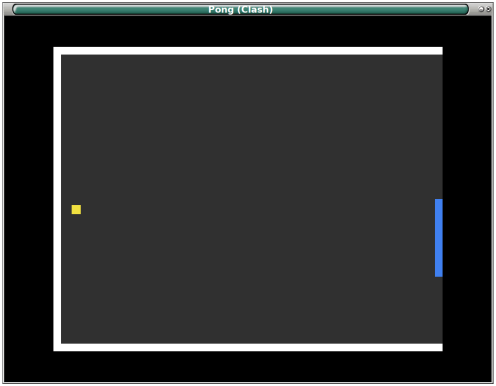
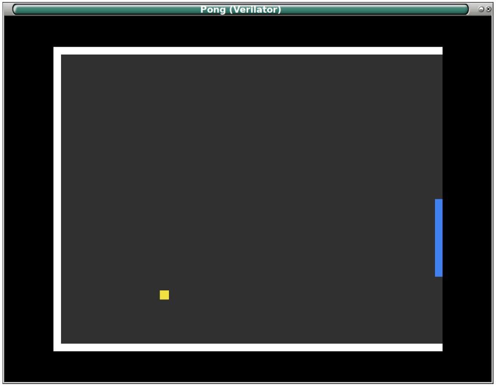


- `signalAutomaton` for periodwise simulation
- VGA signal interpreter

Low-level simulation

- *Broke*: predetermined inputs, batch processing of outputs
- *Woke*: interactive simulation (1/3 fps)
- *Bespoke*: good performance with Verilator (6 fps)



- *Clashilator*: FFI to Verilator simulation
- Simulator UI (incl. VGA interpreter) still in Haskell

Hardware synthesis

- Clash $\rightarrow$ Verilog $\rightarrow$ FPGA bitstream
- Upload to FPGA using vendor tools
- Turnkey build system (`clash-shake`):
  - Papilio One (Xilinx Spartan 3)
  - Papilio Pro (Xilinx Spartan 6)
  - Nexys A7-50T (Xilinx Artix 7)
  - Coming soon: Arrow DECA (Intel MAX 10) by Dylan Thinnes

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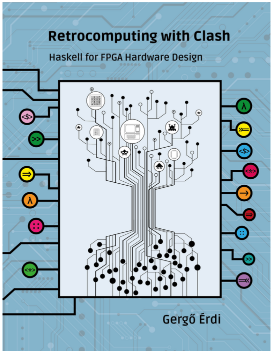
DEMO VIDEO: Pong running on real hardware

Retrocomputing with Clash: Haskell for FPGA Hardware Design

Using Haskell's tools of abstraction to their fullest potential

Full implementation of various fun retrocomputing devices:

- Desktop calculator
- Pong
- Brainfuck as machine code
- CHIP-8
- Intel 8080 CPU
- Space Invaders arcade machine
- Compucolor II home computer



https://retrocla.sh/

Thank you!

Questions?

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