A Call to Action: Accelerating Python with FPGAs
Intro to FPGAs
Field Programmable Gate Array (FPGA), under the hood:

The innards shown here are a simplification of what is inside the actual part.

I/O Cells connect directly to the FPGA chip’s physical pins.
What’s inside?

LUTs, Clocks, PLLs, Transceivers, Multiplexers, Logic Functions, Interconnects, Arithmetic operators and Memories, all GF(2)

Hundreds of thousands of these programmable logic block widgets! They can be interconnected to create logic that can accomplish just about anything. A major part of the device programming involves place and route (the tools do this for you) which is how all the interconnects are setup to put it all together.

Note: logic in ZU3EG is not exactly as shown above but is similar
### Ultra96’s Xilinx ZU3EG PL Internal Attributes:

<table>
<thead>
<tr>
<th>Attribute</th>
<th>103,320</th>
<th>154,350</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Logic Cells</td>
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<td>CLB Flip-Flops</td>
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<td>CLB LUTs</td>
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<td>Block RAM Blocks</td>
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<td>Block RAM (Mb)</td>
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<tr>
<td>Max. HD I/O(^{(2)})</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>System Monitor</td>
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</table>
FPGA Innards:

Raw chip die:
(not actual ZU3EG)

Compiler (synthesis) place and route output:
What can FPGAs (PL) do for me?
The number ONE of many reasons to use FPGA:
Reasons to use an FPGA for your Python:

1. For many solutions the PL will be orders of magnitude faster

2. Precise timing capabilities (picoseconds jitter accuracy) for control of hardware

3. Determinism of algorithmic execution (no cache, preemption, task switching, threads or interrupts if you design it that way)

4. You can do things beyond what the PS can do with Python, even design your own CPU/GPU! See Xilinx’s MicroBlaze™ for PYNQ: https://pynq.readthedocs.io/en/v2.0/pynq_libraries/pynq_microblaze_subsystem.html

5. The art of designing hardware with software can be rewarding and enjoyable!
Other areas where FPGAs excel:

- Reprogrammability allows for in the field upgrades of hardware
- Build your own CPU or GPU: MicroBlaze™, RISC, Custom
- Prototyping for ASICs
- Cellular 4/5G
- Cryptography:
  - AES, Blowfish, Twofish, RSA, Triple DES
- Signal Processing:
  - FIR, IIR, OFDM, FFT, Correlators, CORDIC, Interp, Decimation, NCO, Mixers, Polyphase Filtering, Wavelets
- Digital Motor Control:
  - Servo, Stepper, PWM, PDM
- MIMO
- Prototyping for ASICs
- Cryptocurrencies:
  - BitCoin, Etherum
- GNU Radio
- IoT: read multiple sensors simultaneously
- Digital Signal Processing: Parallel Processing
- Kalman Filtering
- Digital Motor Control: Servo, Stepper, PWM, PDM
- OpenCV
- Scientific Computing
- Cryptocurrencies: BitCoin, Etherum
- Direct control of other hardware
- Machine Learning
- Can be faster than GPUs for some things
- Bridge between CPUs or CPUs and other hardware
- Re-routing hardware signals on fixed PCB for flexibility
- Cellular 4/5G
- Re-routing hardware signals on fixed PCB for flexibility
Use case - Machine Learning computer vision on Ultra96:

- FINN Binary Neural Network (BNN) Demo on Ultra96
- http://www.wiki.xilinx.com/Zynq+UltraScale%EF%BC%8B+MPSoC+Accelerated+Image+Classification+via+Binary+Neural+Network+TechTip

Full 1080p Images per Second in HW: 66.3
Full 1080p Images per Second in *SW: .01

**HW Acceleration Factor: *6171**

* The SW used for benchmark was running on the Ultra96 ARM Cortex™ A53 cores with same OS as the HW tests @ ~1.3GHz. Other platforms that have somewhat faster ARM cores could do a little better with just SW. Other platforms with their own hardware accelerators will also run faster than pure SW.
Use case - Matrix Multiply Algorithm Acceleration

- 32x32 Matrix Multiply of floats
- Algorithm developed in C
- Then accelerated in programmable logic
- Python can make calls into the C code for this

<table>
<thead>
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<th>Processor-only Cycles</th>
<th>Accelerated Cycles</th>
<th>Acceleration</th>
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Daniel Rozwood -- Ultra96 SDSoC Platform for v2018.2
<table>
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<tr>
<th>Domain / Topic</th>
<th>Title / Author / DOI</th>
<th>Improvement vs CPU+GPU</th>
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<td>Machine Vision Moving Average with Local Difference (MALD)</td>
<td>CPU, GPU and FPGA Implementations of MALD: Ceramic Tile Surface Defects Detection Algorithm, Hocenski, <a href="http://dx.doi.org/10.7305/automatika.2014.01.317">http://dx.doi.org/10.7305/automatika.2014.01.317</a></td>
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<td>Bioinformatics De Novo Genome Assembly</td>
<td>Hardware Accelerated Novel Optical <em>De Novo</em> Assembly for Large-Scale Genomes, Kastner, <a href="http://dx.doi.org/10.1109/FPL.2014.6927499">http://dx.doi.org/10.1109/FPL.2014.6927499</a></td>
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<td>Atmospheric Modelling Solvers for Global Atmospheric Equations</td>
<td>Accelerating Solvers for Global Atmospheric Equations through Mixed-Precision Data Flow Engine, Gan, <a href="http://dx.doi.org/10.1109/FPL.2013.6645508">http://dx.doi.org/10.1109/FPL.2013.6645508</a></td>
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Ultra96 tools intro
Vivado HLx IDE for Ultra96 PL:

- Vivado is the main Xilinx tool that converts RTL source code files into FPGA hardware
- It is a GUI project manager
- Performs hardware verification and debugging
- Tallies and manages the internal FPGA resources
- Allows for schematic block based hardware design
- Exports and imports to many other Xilinx tools
- Performs power consumption analysis for the ZYNQ MPSoC
- Generates the bitstream/overlay files used for programming the PL
- Accepts C/C++ and converts it into hardware: High Level Synthesis (HLS)
Vivado HLx IDE for Ultra96 PL:

Hardware describing source code

FPGA bitstream (like a binary)
Vivado HLS for PL design:

- HLS allows one to create hardware with C/C++ but...
- It does not handle moving the data between the PS and PL for you, this may be what you want anyways especially if you are using a stand-alone FPGA or PYNQ moves the data for you, it depends
SDSoC for Ultra96 PS and PL:

- SDSoC is a separate GUI from Vivado
- Converts your C/C++ into a hybrid system using both the PS and PL
- It moves the data between the two for you and creates PL!

C/C++ → bitstream + .exe, .so
XSDK tool for Ultra96 PS:

- XSDK is an eclipse based front end for software development on the PS
- XSDK can edit compile and debug C/C++
- XSDK can also program ZYNQ parts
PetaLinux for Ultra96

- aarch64 Linux Kernel
- Embedded Linux with Xilinx enhancements made to run on the ZU3EG
- Simple and time saving Xilinx ‘petalinux-’ cmds to drive Yocto
- Yocto based configuration and development tools
- Multiple choices for root FS, including ram based, PetaLinux, Debian and Ubuntu
- Integrates with PL hardware designs
FPGA Hardware Design Languages (HDL):

- Not that long ago hardware designers had fewer choices for PL programming languages, one of which was VHDL.
- Designers involved with ASIC design often use a language called Verilog, FPGAs can also be programmed using it.
- These languages work very well and are still supported. They are elegant and very powerful but less people are familiar with them compared to Python or C/C++.
- Xilinx reached out to the software community and created tools to allow them to design hardware using C/C++: SDSoC and HLS.
- There is also a 3rd party project that allows hardware design using Python itself. See http://www.myhdl.org
- Xilinx also allows hardware design using drag and drop blocks, this is referred to as IP Integrator.
Configuring the FPGA (NOT designing the HW):

1. Write your code to define the hardware using your preferred method.
2. Use the FPGA compiler (HLS, SDSoC, VHDL, Verilog, GUI Block Design) running on a PC to map your design for you into the internal logic blocks and interconnects.
3. The final output from the FPGA compiler will be a file that contains the information to configure the device. This is called a bitstream file in the PYNQ context it will be called an overlay.
4. The bitstream file will need to be transferred from the PC to an external CPU or ZYNQ device and then to the PL portion of the device using a precise protocol. Xilinx details this protocol and provides tools to configure the ZYNQ devices. This is called configuring the FPGA and is analogous to a software OS loading and running an .exe.
Python and FPGAs
Traditional context for full Python systems:

- **Your Python Source**
- **Python libraries**
- **iPython/cmd-line/Aconda/Idle/Jupyter**
- **Python engine**
- **OS (PetaLinux, Windows, OSX, Linux etc.)**
- **HAL**
- **CPU + Memory + I/O + Storage = Computer (PC, Server or Embedded)**
- **Libraries from other languages**
In the beginning (and still an option - 2 separate devices):

**PS - CPU**
(x86, ARM, MIPs, 68000, PIC, PowerPC, AVR)

Each CPU can require a different bus, yes but the FPGA is programmable. This is a lot of work each time.

**PL - FPGA**

But plain FPGAs don't come with much of any built-in data bus, you must construct your own from the programmable hardware!

If I want to use the PL on the data I have to get my data from the CPU to it via a physical data bus of some type.

**PS = Processing System**
Python data to bits and back again:

Python running on PS - CPU

Data Bus

PL - FPGA

FPGAs great at bits but not as good at directly handling high level Information!

Python handles data representing information great but not as good at bits!

Various Python to C conversion techniques exist: CFFI, c-types, Cython, spam etc. Use your favorite.

From C/C++ you can then easily do bits and talk to hardware like the FPGA
Ultra96 PS + PL all in one ZYNQ device:

Enter Ultra96’s ZU3EG ZYNQ UltraScale+ MPSoC

The bus between the CPU and FPGA are in the same chip and Xilinx has designed the data bus between them for you.

**PS** = Processing System

**PL** = Programmable Logic (FPGA)
Python on Ultra96 PetaLinux Platform:

CPU + Memory + I/O + Storage = Computer (PC, Server or Embedded)

Programmable Logic (PL) / FPGA

Your Python Source

Python libraries

iPython/cmd-line/Jupyter

Python engine

OS (PetaLinux)

HAL

Libraries built with other languages

= Layer modified to support PL

= Layer may have to be modified to support PL (Depending upon approach)
An easier path - Xilinx PYNQ™ for Ultra96:

- **What is PYNQ?**
  
  An open source software framework designed to make Ultra96 more Python friendly and easier for Python to interact with the PL on embedded system platforms. It is comprised of:
  
  - PetaLinux (aarch64 kernel)
  - Ubuntu Bionic root file-system
  - Full Python (as opposed to Micro Python)
  - Jupyter Notebooks
  - Python libraries for using the Xilinx PS and PL

- **Why would I want to use it?**
  
  Has the ability to make some of your slow Python programs run FAST, really really FAST and allows Python to control hardware that other platforms could only dream about. It can also dramatically reduce design time and effort!
What PYNQ does for you:

Provides a Python “pynq” library with the following helper functionality:

- HW Interrupts
- Manipulate hardware pins
- Map physical memory into Python for PL/PS xfer
- Overlay – program the FPGA bitstream from Python
- Read various PS and PL attributes
- Utilize DMA to move data between PL and PS
- Primitives to help accelerate parts of numpy
- pynq.lib contains objects to manipulate some of the board’s external hardware and operate custom MicroBlaze™ CPUs in the PL.

Read all about it:
https://pynq.readthedocs.io/en/v2.2.1/pynq_package.html
Python on the Ultra96 PYNQ Platform:

- Your Python Source
- Python libraries
- iPython/cmd-line/Jupyter
- Python engine
- OS (PetaLinux)
- HAL

CPU + Memory + I/O + Storage = Computer (PC, Server or Embedded)

Your PL Stuff

- Libraries built with other languages

= Layer modified for you
= You still need to modify
Great place to start: www.pynq.io/community.html

Tutorials and other resources

**Tutorial: HLS filter example**

How to Use a HLS Core in PYNQ

1. Downloading Dependencies
2. Creating a Vivado HLS Core
3. Building a Vivado Bitstream
4. Using an HLS Core in PYNQ
5. Packaging an Overlay

At the end of this tutorial you will know how to:

1. Package a Vivado HLS Core with AXI Interface as a Vivado
2. Build a Bitstream in Vivado HLS
3. Interact with an HLS Core in PYNQ
4. Package, Install, and Load a custom PYNQ overlay

**Video: Custom HLS adder IP**

**Video: Accelerate FIR software function**

**Video: Add existing IP to a PYNQ overlay**

**Video: Control custom IP using GPIO**
Great place to start: www.pynq.io/community.html

Community Projects

A selection of projects from the PYNQ community is shown below. Note that some examples are built on different versions of the PYNQ image.

- spoonNN
  ETH Zurich
  FPGA-based neural network inference project

- iSmart DNN
  FPGA-based neural network inference for DAC 2019 contest

- TGIIF
  1st place in the DAC 2018 design contest for neural network object detection

- cv2PYNQ
  FAU
  Accelerated OpenCV image filtering library

- Video processing
  KU Leuven
  Hardware accelerated videoprocessing

- ZipML-PYNQ
  ETH Zurich
  Hardware accelerated compression

- PYNQ bot
  IT Tallaght
  Control of robotic car from PYNQ

- PYNQ LED cube
  Fudan University, Xilinx China
  Controlling an LED cube from PYNQ
When will Xilinx PYNQ™ be available for Ultra96?

- PYNQ for Ultra96 is coming soon, expected 1st week of Oct. 2018!!

http://zedboard.org/product/ultra96

Ultra96 PYNQ platform will be hosted on Avnet’s github:
http://github.com/Avnet
Summary of Accelerating Python development workflow:

1) Determine what functionality you want to accelerate in the PL

2a) Develop or port the selected algorithm with VHDL, Verilog, MyHDL for the PL

2b) Develop or port existing algorithm in C or C++

3a) Create your own system to move data between PS and PL

3b) Use HLS to create the PL hardware

3c) Use SDSoC to move the data between PS and PL for you and also create the PL hardware

4a) Use PYNQ Python modules to exchange data with the PL

4b) Choose your own method to interface Python to the PL

+ = Can be tied in to PYNQ supported data movers
- = PYNQ can coexist or still help

AVNET
Acquire your own Ultra96 board for $249:

http://zedboard.org/product/ultra96

Includes:
- Ultra96 development board
- 16 GB pre-loaded MicroSD card + adapter
- Voucher for SDSoC license from Xilinx
- Quick-start instruction card

Does not include (but necessary):
- External 12V 2A 96boards adapter

Optional Accessories:
- Seed Studios Grove Starter Kit for 96boards
- Other compatible accessories
- JTAG to USB adapter board
Acknowledgements:

THANK YOU for attending!

Much gratitude to my friend Aron Khan who weathered v1.0 of my presentation and offered very useful advice to improve it.

A special salute to all the folks in the trenches who carry the PYNQ flag, especially:

Dr. Yun “Rock” Qu PhD, Dr. Graham Schelle PhD, Cathal McCabe, Peter Ogden, Anurag Dubey

And thank you to the following people who also helped provide for the opportunity to share this with you:

Avnet: Kevin Keryk, Bryan Fletcher
Get more help on PYNQ™ and Python for Ultra96:

PYNQ Workshop: https://github.com/Xilinx/PYNQ_Workshop

See other’s examples (Ultra96 examples will be added soon): http://www.pynq.io/community

See Avnet’s Ultra96 tutorials (more on the way): http://zedboard.org/support/design/24166/156

Join Xilinx’s Developer Zone to access free tools: https://www.xilinx.com/products/design-tools/software-zone.html