



OpenCPI - Open Component Portability Infrastructure

**An Open Source Infrastructure for
Heterogeneous/Embedded Component-
Based Systems and Applications**

**Introduction to OpenCPI Platform
Development**

Summary of OpenCPI Development

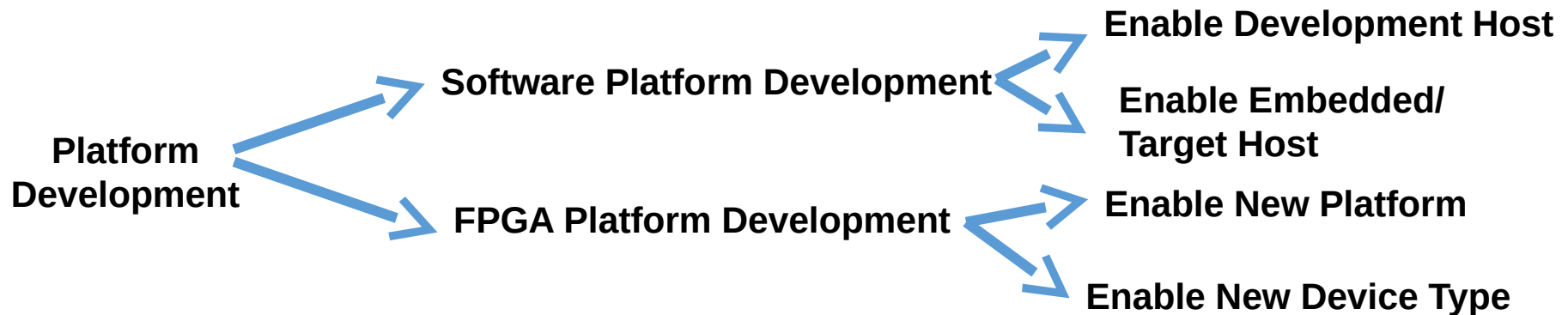
Roles

Three types of development with common XML-driven workflow

	Application Development	Component Development	Platform Development
Objective	<ul style="list-style-type: none">• Create applications using components	<ul style="list-style-type: none">• Create building blocks for applications	<ul style="list-style-type: none">• Create infrastructure for running applications
Examples	<ul style="list-style-type: none">• Tb_bias• FSK app	<ul style="list-style-type: none">• Bias• FIR filter	<ul style="list-style-type: none">• Zedboard• Transceivers
Key functions	<ul style="list-style-type: none">• Declare components and their connections and properties	<ul style="list-style-type: none">• Process data and interface between other components• Vendor agnostic (ideally)	<ul style="list-style-type: none">• Provide interface to software and FPGA peripheral (devices workers)
Skills Required	<ul style="list-style-type: none">• Familiarity with component library	<ul style="list-style-type: none">• S/W: C, C++• H/W: VHDL	<ul style="list-style-type: none">• H/W: VHDL• Strong knowledge of platform architecture and interfaces
Knowledge of OpenCPI build flow			

- Review of Terminology
- Systems vs Platforms $\Rightarrow$ Platform Development
- Enabling a new System (What's the process?)
- Enabling Development Hosts (new Operating System)
- Enabling GPP (General Purpose Processor) Platforms
- Enabling FPGA (Field Programmable Gate Array) Platforms

Enabling new platforms and devices for OpenCPI apps



Terminology Review

- Component – a "promise" of a function where properties and ports are defined
- Application – a set of connected components
- Platform – a processor and its directly-connected hardware
- System – Platforms connected by interconnects, used for running component-based applications
- Interconnects – signaling (control/data) paths that connect platforms
- Processor – an integrated circuit capable of executing a component-based application
- Application Worker – a component implementation that requires only abstracted data interfaces
- Container – execution environment on a processor that will execute workers
- Platform Configuration – a unique configuration of devices on a platform
- Control Plane – Worker "LifeCycle" and "Property" access
- Data Plane – Container Data (DMA) Engine, "Ports" and "Protocols"
- Device Worker – an HDL component implementation that interfaces with I/O devices that are FPGA-external
- Platform Worker – Special type of device worker
- HDL Assembly (sub-assembly) – a set of connected HDL application workers

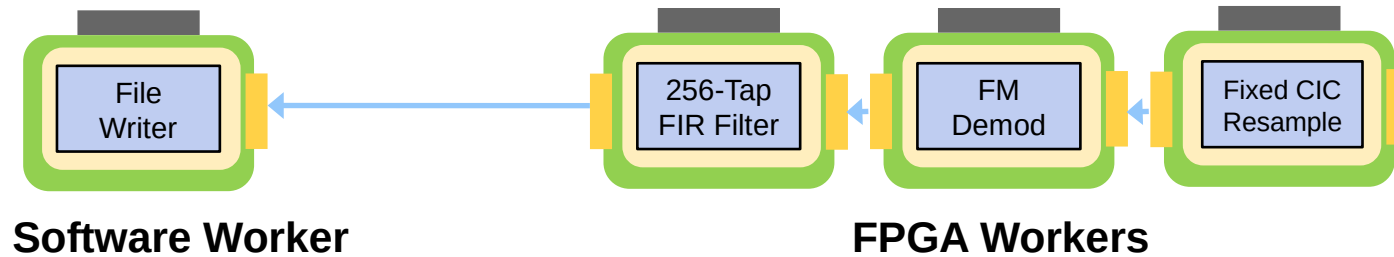
See the [OpenCPI Glossary](#) for detailed definitions of OpenCPI and related industry terminology

- Terminology Review
- **Systems vs Platforms $\Rightarrow$ Platform Development**
- Enabling a new System (What's the process?)
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- **System** – a collection of processing elements (**Processor**) that can be used together as resources for running component-based applications.
- **Platform** – a **Processor** and its surrounding directly-connected hardware (memory and I/O devices).
- **Interconnect** – data paths that allow platforms to communicate with each other.
- Instead of enabling a "system", OpenCPI focuses on enabling each "platform" and "interconnects" within a system.
- Hence **Platform Development** is enabling a platform, and enabling a system is enabling whatever platforms and interconnects are in the system.

What is an OpenCPI FPGA Platform?

- An **OpenCPI FPGA Platform** is the FPGA, its surrounding infrastructure and attached devices.
- *Enabling the platform* allows it to be used for an OpenCPI application.
- Put another way, what do I need to run an OpenCPI app?

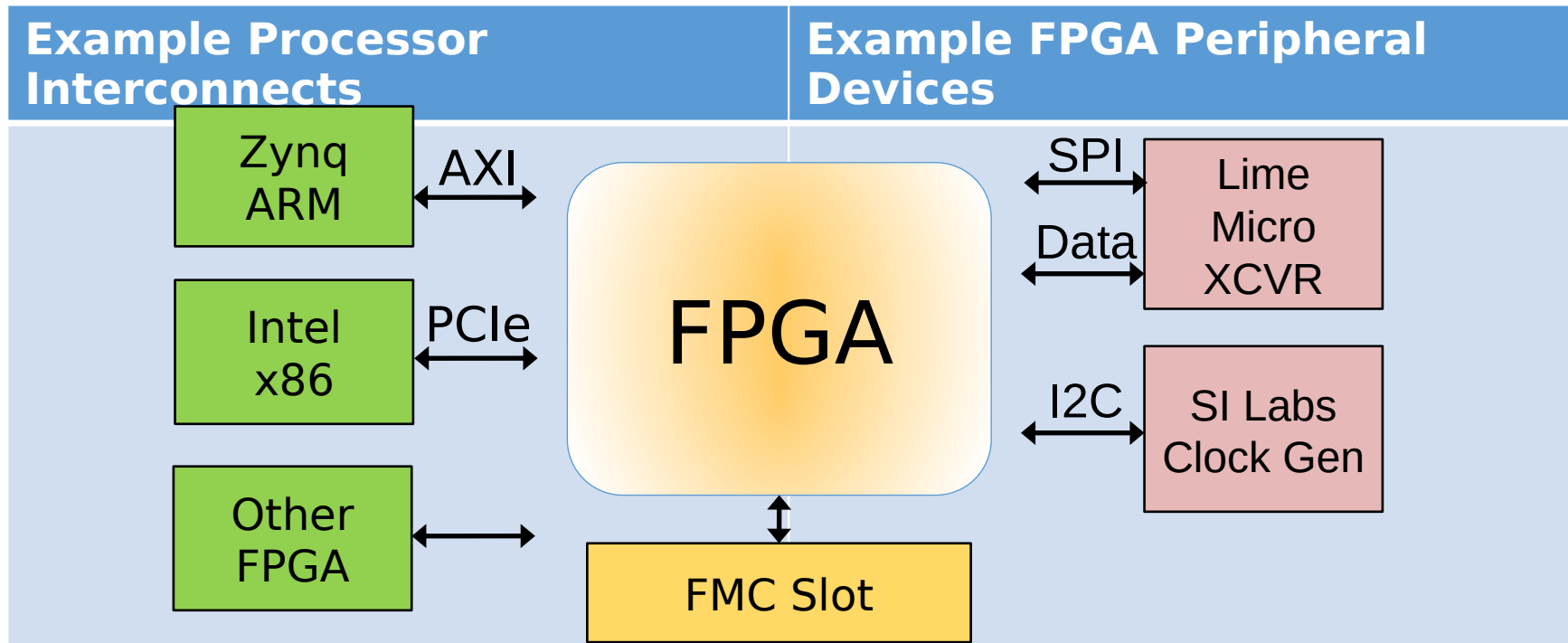


on *my* hardware?



Review: Pieces of OpenCPI Platforms

1. **The FPGA:** a place where HDL application workers may execute
2. **Interconnects:** off-chip connections to processor(s) or other FPGA platforms
3. **Devices:** peripherals attached to the FPGA, useful to applications
4. **Slots:** hardware physical interfaces where **cards** (with devices) are plugged in



An OpenCPI platform consists of a **Processor** with **Interconnects** allowing it to communicate with other platforms and two additional elements:

- **Devices**

- Hardware elements locally attached to the processor
- Allow source or sink of data flowing between components to enter or exit a system

- **Slots (& Cards)**

- A means to support add-on **cards**
- **Cards** – When plugged into a platform's slot, a card declares the use of additional devices

- Common CPU, Intel or AMD x86 on a motherboard
 - If cards are plugged into slots on the PC's motherboard, and those cards have **processors** (e.g. GPP, FPGA), then those cards can act as additional **platforms** in that **system** (e.g. Xilinx Artix 7 Series PCIe-based development boards)
 - Multi-core GPPs are single "processors" since they generally run a single operating system and act as a single resource that can run multiple threads concurrently
- ZedBoard from Digilent, based on Xilinx Zynq device
 - "System-On Chip" (SoC)
 - Two **processing** (aka **platforms**) elements: Dual-core ARM and FPGA
 - **Interconnects**: AXI-4 interfaces (Master: GP 0/1, Slave: HP 0-3)
 - **Devices**: memory, pushbuttons, etc
 - **Slots**: FMC-LPC

Every platform must be enabled for:

- Development - the process of producing "executable binaries"
 - Requires integrating compiler tool chains into OpenCPI's build framework
 - Typically requires scripts or wrappers to enable tool operation within OpenCPI
 - Does not preclude or require GUI-based IDEs in the development process
 - Cross-compilers are leveraged for supporting embedded systems
- Execution – the process of running those binaries on the available platforms in a system

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- Enabling **systems** implies enabling **platforms** and **interconnects** in the system, as well as enabling **processors** and **devices** on the platforms and devices on any **cards** used in the system.
- What are the steps?
 - System Inventory – Which elements are relevant?
 - Assessment – What's the current level of support?
 - Additional System-Level information
 - Experiments to fill in the knowledge gaps

Identify hardware elements relevant to component-based applications:

- Processors, aka "Containers"
 - Elements capable of executing a worker
 - CPU - Intel AMD x86_64, Zynq-7000(ARM)
 - FPGA - Zynq-7000(PL), Zynq-Ultrascale(PL)
- Interconnects
 - Physical paths which connect Processors (PCIe, Ethernet)
- Devices
 - Devices connected to Processors
 - Examples: SPI, I2C, ADC, DAC, custom, memory, temperature, GPS

Assessment: Current Level of Support

For each:

- Processor
 - What is the current level of support by the framework? Is it already present, a variant, a new processor, or a new class of processor?
 - What is the current level of support by the tool chain?: Is it already present, does it require an update/variant, or is it missing?
- Interconnect – for each processor type that is attached to it
 - What is the current level of support by the framework? Is it already present, does it require enhancements, or is it missing for the processor type?
- Device
 - What is the current level of support by the framework? Is it already present, does it require enhancements, is it missing but similar to supported devices, or missing?

Gather/Create Technical Data Package

- Data sheets, ICDs, schematics, Connectivity (pinouts), signal timing, and memory maps
- Description of functions for each element
- Description of power sequences, boot sequences, initialization, reconfiguration, calibration, operation
- Event driven actions
 - *E.g.*, temperature thresholds cause a throttling of the processors
- Timing
 - Oscillators drive synchronization (SW/HW) circuits, control and data clocks, etc.
 - Synchronization with GPS or reference clocks (1PPS, 10MHz distro)
 - Special calibration sequences
- Non-volatile media, removable media
- How are reprogrammable device programmed? (CPU, boot flash, JTAG)
- Debug ports
- Are there any "white wires" or other hardware errata?

Gaps

- Reasons for performing experiments:
 - Uncertainties and gaps in technical documentation
 - Information is unavailable due to proprietary restrictions
 - Verify functional or performance capabilities of the system that are missing or questionable from the gathered information
 - Reverse engineer missing ICD aspects (assuming no legal impediments)

These efforts establish the final information to plan and budget for enabling a new system.

- Planning and Specification – Define requirements and tasking
- Technical Development – Execute tasks
- Verification – Testing
- "Contribute" – Back to OpenCPI repository to benefit others

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All steps shall be recorded for reproducibility!

1. Install OS with suitable options and packages
2. Install native development tools to drive OpenCPI's build system
3. Retrieve current source code for OpenCPI

THE NEXT STEPS ARE THE SAME AS THOSE FOR SUPPORTING ANY RUNTIME PLATFORM AND ARE EXPLAINED IN THE NEXT SECTION "Enable GPP Platforms".

4. Establish a build environment with appropriate options
5. Build the core OpenCPI software targeting the development host
6. Build/Test OpenCPI component libraries and example applications

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Two aspects:

- Development/Cross development
 - Building component and application binaries for the target platform
- Execution
 - Building the core OpenCPI runtime libraries and runtime command line utilities for the target platform

- Whether the GPP is native to the development host, or on an embedded system, the tool chain must be integrated into the OpenCPI build process
 - Cross-compilers are used for embedded systems
- Where is my compiler coming from?
 - Development host's globally installed default tools, e.g. Rocky9, Ubuntu22.04
 - A unique prerequisite installation in OpenCPI's own installation tree (e.g. specific compiler dependency)
 - A "side-effect" of another tool installation, ex. Xilinx Zynq SOC (FPGA + dual core ARM)

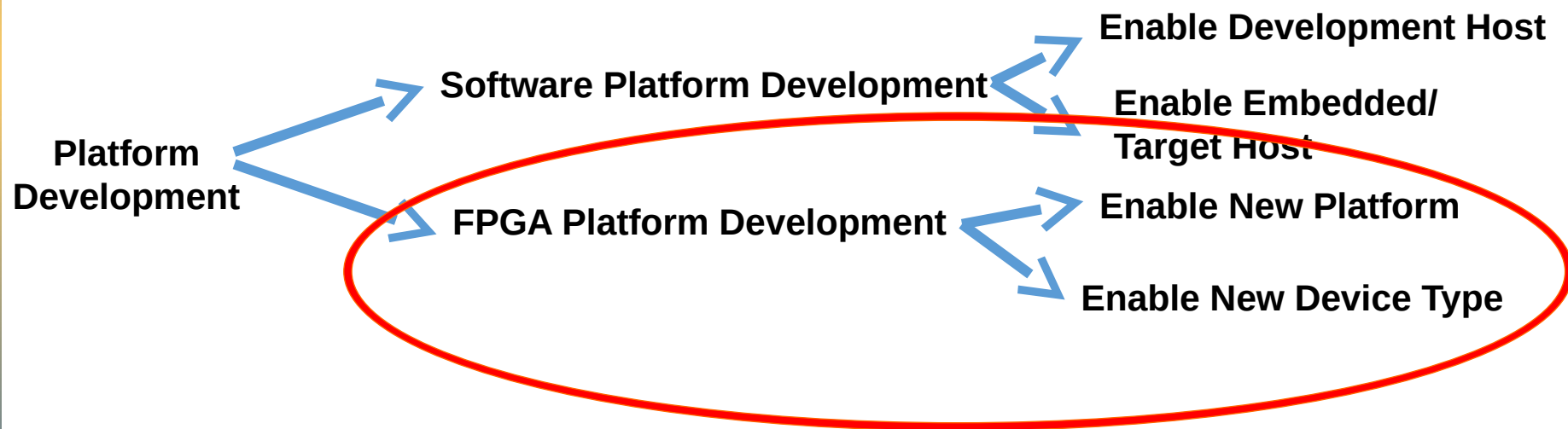
- Requires building the framework using the appropriate [cross-]compiler for the target GPP platform
 - Command line tools
 - Libraries
 - Device drivers
- Several runtime libraries have conditional compilation depending on the system or CPU being targeted
 - Significant Linux dependencies

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- **Enabling FPGA (Field Programmable Gate Array) Platforms**

- Two aspects enable an FPGA platform:
- Need to understand "What is an OpenCPI..."
 - ...FPGA Platform?
 - ...FPGA Platform Infrastructure?
 - ...Platform Worker?
 - ...Device Worker?
 - ...Slot?
 - ...Platform Configuration?
 - ...Container/Bitstream?
- Case Study:
 - Epiq Matchstiq-Z1 SDR
 - Device/Proxy Workers to support Lime Microsystems Transceiver

Types of OpenCPI Platform Development

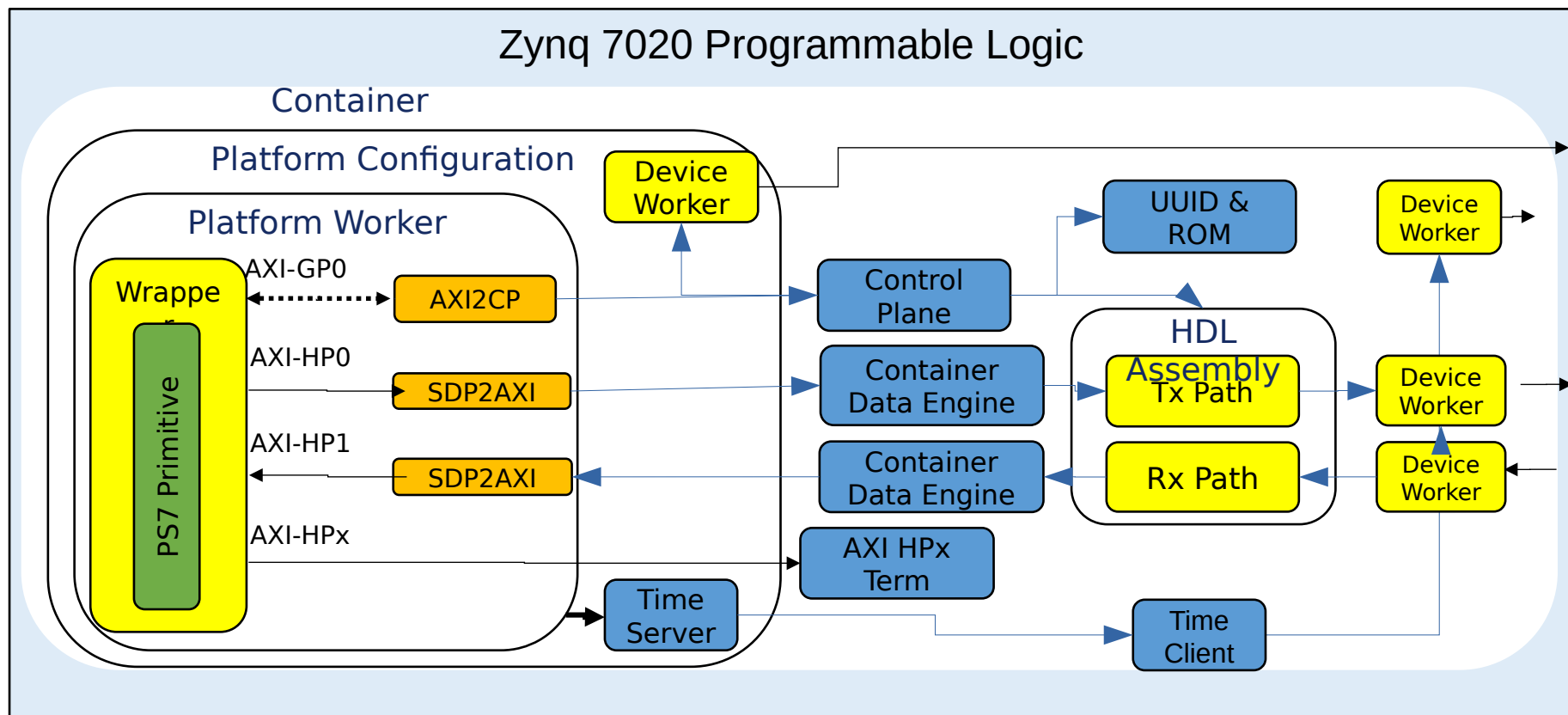
Enabling new platforms and devices for OpenCPI apps



Similar to enabling a GPP, there are two aspects to enable an FPGA:

- Development environment - What do I need to build?
 - Installation and integration of tool chain to target (build) the FPGA on the platform and core OpenCPI HDL code
- Execution - What do I need to run?
 - Writing specific new HDL code that supports the particulars of the hardware attached to the FPGA (except for simulator)
 - Verifying reference test applications on the platform

Block Diagram of a Zynq 7000-based FPGA Design in OpenCPI



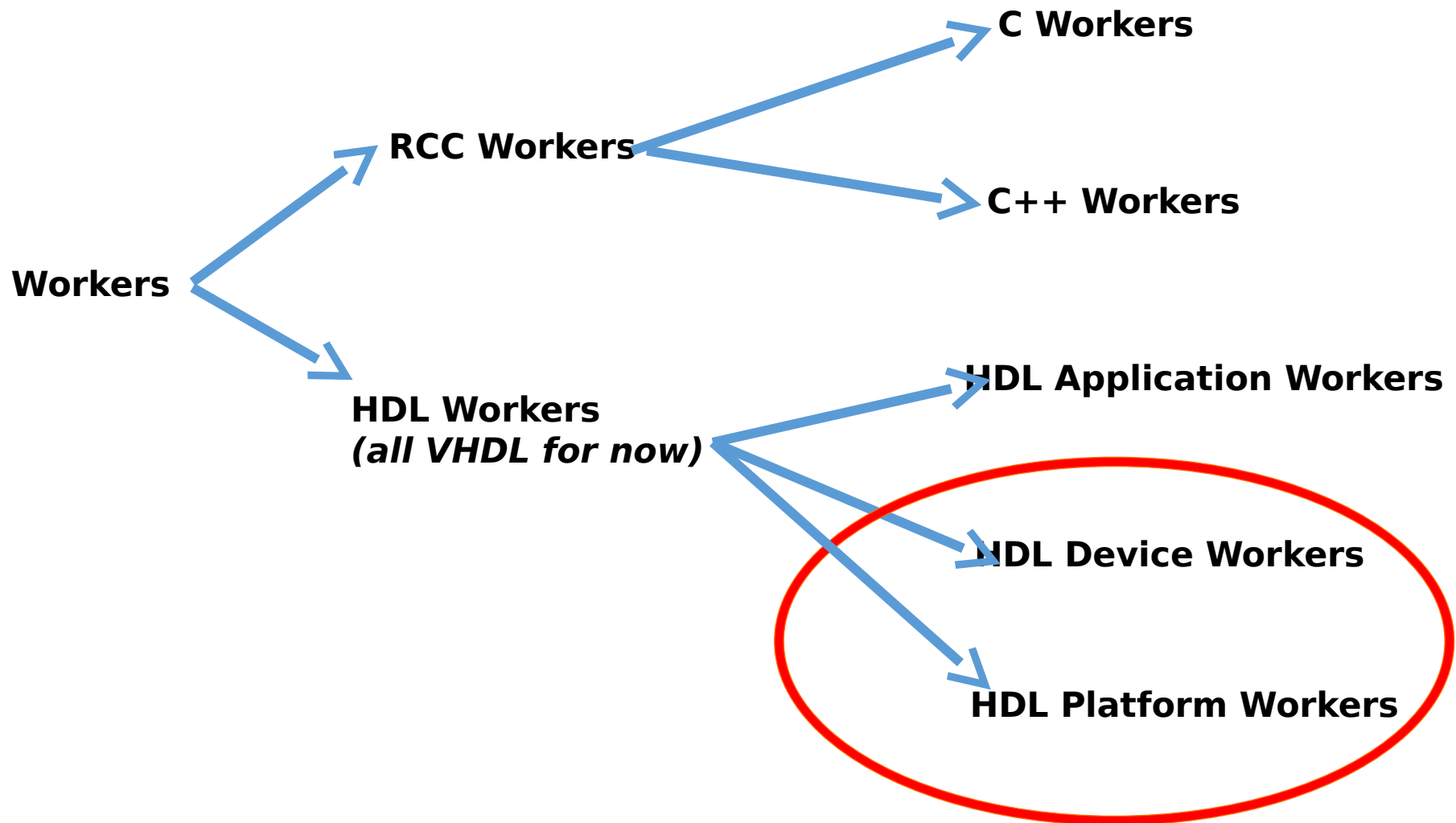
Generic Infrastructure included with OpenCPI – instanced by platform developer

Generic Infrastructure included with OpenCPI – automatically instanced and connected, as needed, by the code-generation tool

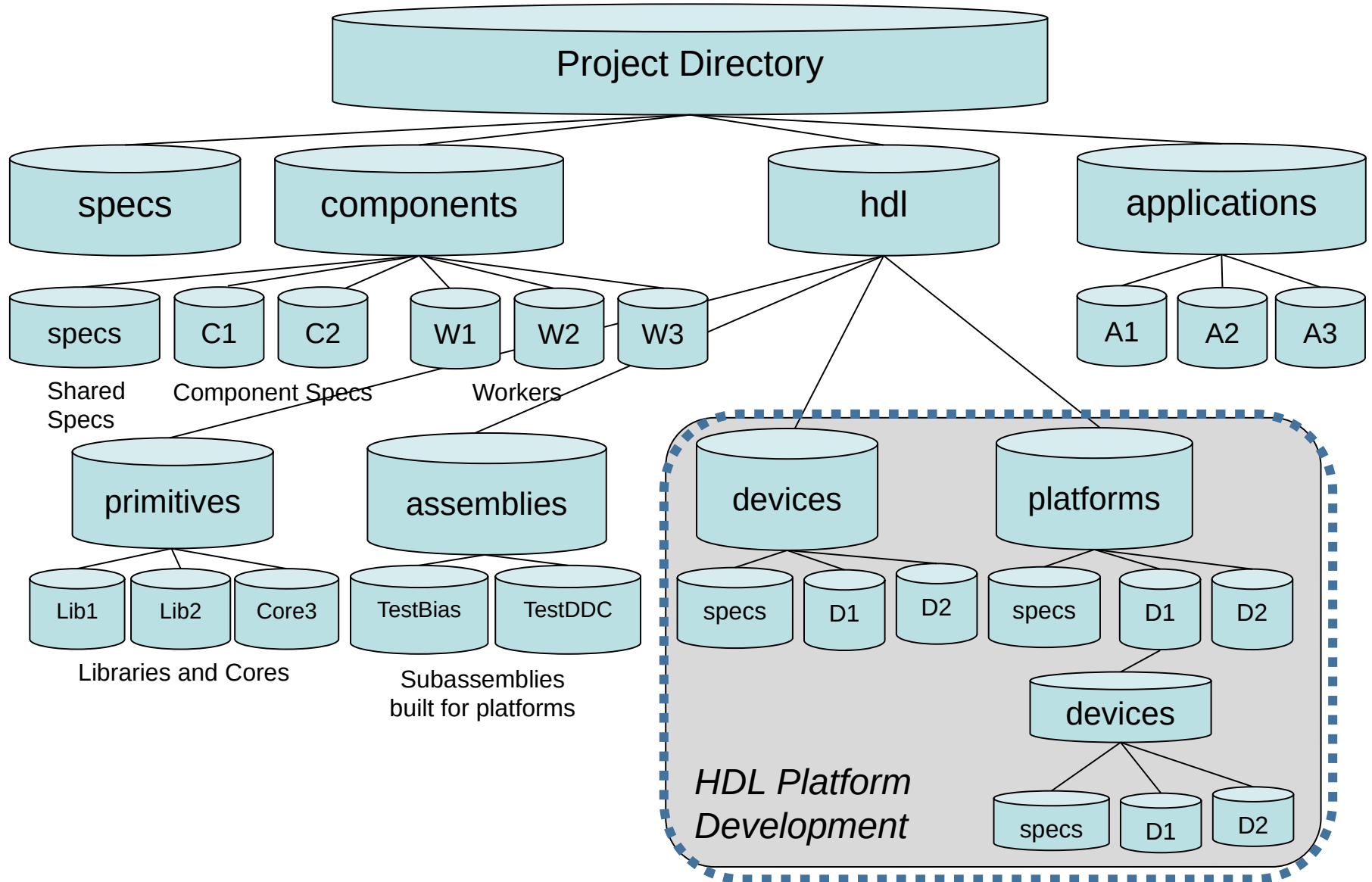
Vendor supplied hard IP block

Custom code required for platform enablement

Types of OpenCPI Workers



Project Directory Layout

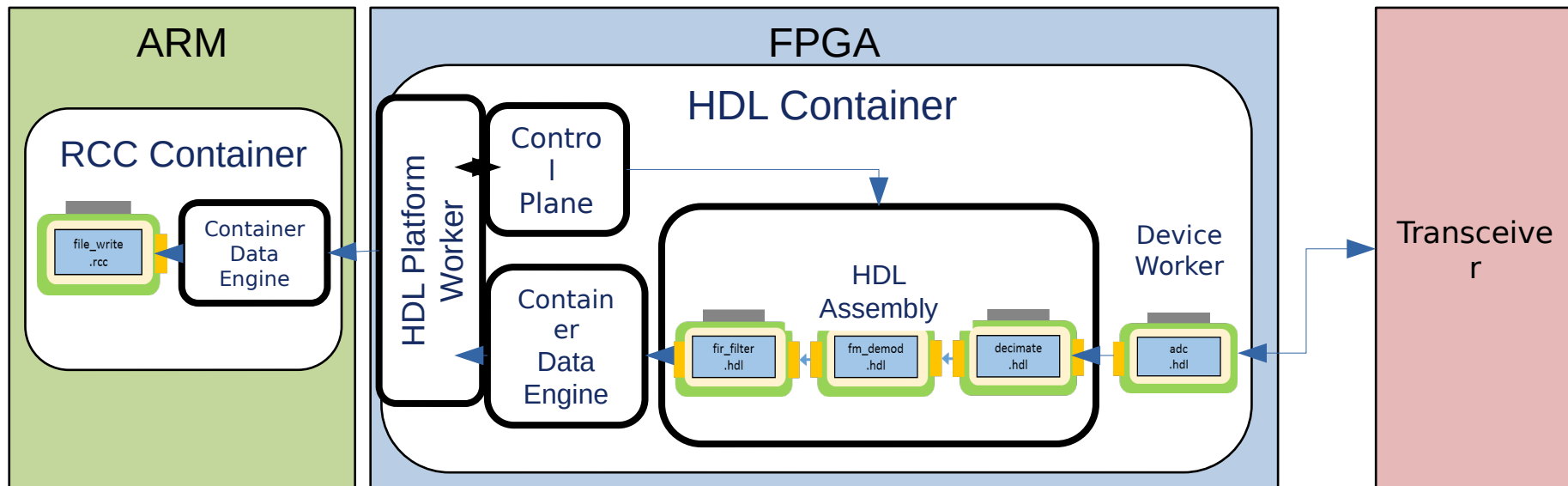


What is an “OpenCPI FPGA” Platform?

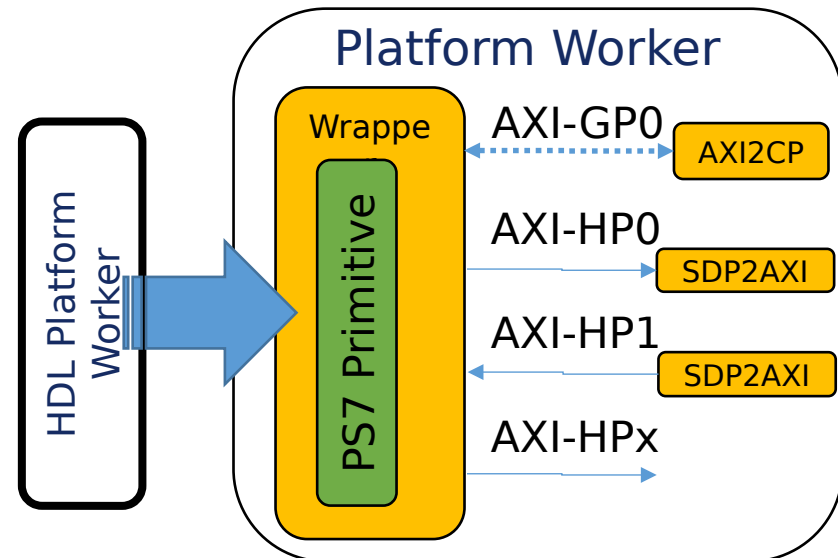
- A single FPGA on some board that has the infrastructure to serve as an OpenCPI Container to a component-based application
 - May have Devices and Slots
 - Ex. E310 (Zynq 7020), ZedBoard(Zynq 7020), PicoEVB (Artix7)
- If a board has multiple FPGAs, then *each one* is an OpenCPI FPGA platform
 - Provided that enough resources remain after the OpenCPI infrastructure is in-place and the proper interconnects are present
 - Note: At this time, there are no working examples of platforms with multiple FPGAs
- An FPGA simulator is an FPGA platform
 - Where HDL components may execute, with all the same infrastructure as physical FPGA platforms ("co-simulation") or a "bare-bones" infrastructure environment

What is “OpenCPI FPGA Platform Infrastructure”?

- Typically comprised of the following OSS IP HDL modules
 - Platform Worker – Adapter for interfacing with Interconnects and internals
 - Control Plane – Local bus to interface with a workers control port
 - Data Plane – Pathways for workers to exchange data, and where the Container Data Engine(s) are used to pass data on/off the FPGA



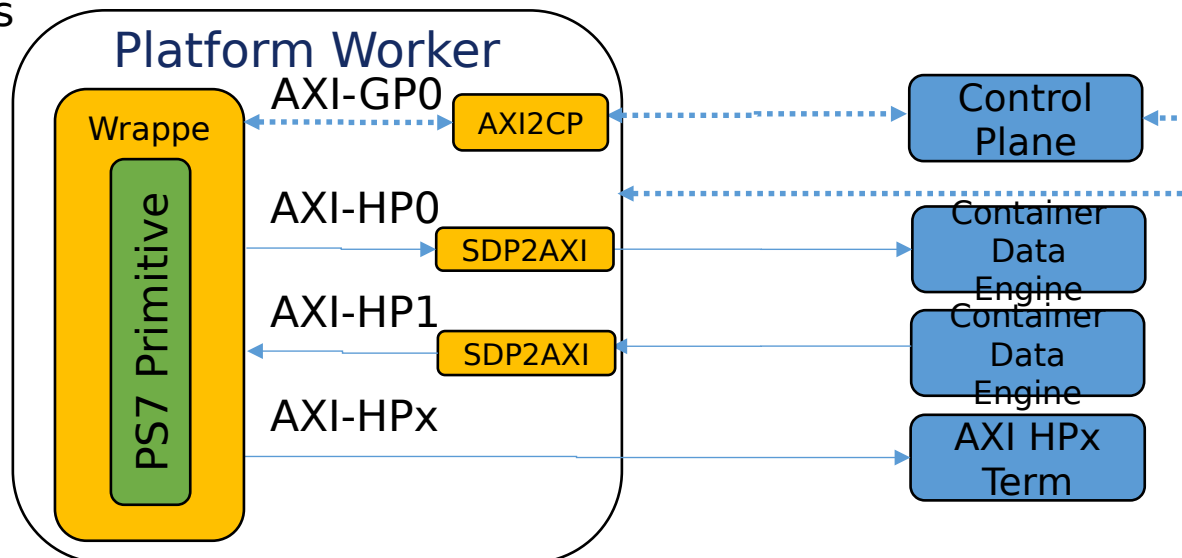
- A specific type of HDL Device Worker that describes additional information regarding hardware aspects of the platform
 - System-time, control, data
- Provides infrastructure to adapt external interconnects to the internal control/data interfaces of the FPGA
- Implements Platform Spec (OCS)
 - `<ocpi-install-path>/projects/core/specs/platform-spec.xml`
- Defined by XML and VHDL



- Like all workers, the HDL Platform Worker has an OWD that defines requirements for the code-generation tool `<HdlPlatform>`.
 - Configure platform `<SpecProperty>`, e.g. platform name
 - Define properties `<Property>`
 - Declares signals (similar to Device Worker!) `<Signal>`
 - Declares capabilities that are unique to HDL Platform Workers
 - Master of `<metadata>`, `<timebase>`, control plane `<cpmaster>`, data plane `<sdp>`
 - Declare and parameterize frequency with which to operate time service module
 - Declares all possible `<Device>` workers that are available in support of the platform
 - Does not mean that they will be built into bitstream, but required for the build engine
 - Defines Slots(s) `<Slot>`
 - Signal re-mapping: platform signals to slot signals (and possibly device signals)
 - Defines Dev-Signals which are signals connected between device workers `<DevSignals>`
- The OWD is part of the HDL Platform Worker's OpenCPI HDL Platform Description (OHPD) XML file, which also describes the devices (controlled by HDL device workers) that are attached to the HDL platform and available for use.
- Unlike App/Device Workers, HDL Platform Workers do not support DataInterfaces

HDL Platform Worker: VHDL

- Instances modules to adapt external Interconnects to internal control/data mechanisms
- System-level: reset and clocking (control plane and time server)
- PCIe-based platforms instance a vendor PCIe IP block (ex. Xilinx Block Plus Endpoint) module and an OpenCPI IP uNOC (micro-Network On A Chip) and adapters are used to convert the PCIe to the Control Plane and Container Data Engines
- Zynq-based platforms instance a processor module and OpenCPI IP adapters to convert AXI to the Control Plane and Container Data Engines infrastructure modules



Control Plane

- Platform-independent HDL module for reading and writing properties for all three types of HDL workers: App, Device, Platform
- Instanced in the auto-generated Container VHDL
- Scales according to the number of workers in the Container
- System-level provider of reset and clock for all workers (adapters)
 - HDL Platform Worker sources reset and clock to Control Plane, then Control Plane sources to workers' control interfaces
- `<ocpi-install-path>/projects/core/hdl/primitives/platform/ocscp_rv.vhd`

- Portable framework modules for moving data between workers and to/from containers
 - Container Data (DMA) Engine per stream
 - uNOC/SDP for multiplexing streams (maybe control plane) into an interconnect channel
 - HDL Platform Worker's adaptation of these "interconnect access channels" to the system interconnect

Slots (and Cards)

- Defined by XML (no HDL code)
- Characterized by
 - Physical connectors
 - Electrical signaling and direction
 - Pin and signal name assignments
- Example of common types (hdl/cards/spec/)
 - FMC (FPGA Mezzanine Cards, as defined by VITA 57 standard)
 - fmc_lpc.xml, fmc_hpc.xml
 - HSMC (High Speed Mezzanine Cards, as defined by Altera)
 - hsmc.xml

Cards (and Slots)

- Defined by XML (no HDL code)
- Instances additional HDL Device Worker(s) that may be plugged into a Slot on various platforms
- Therefore, devices may be directly attached to the pins of the platform FPGA, or they may exist on a plug-in card, that, when plugged into a slot, become attached to the platform FPGA
- Example of common types (hdl/cards/spec/)
 - Analog Devices FMCOMMS3_EBZ
 - fmcomms_2_3_hpc.xml, fmcomms_2_3_lpc.xml

- XML that defines an HDL platform with a particular set of devices
 - Top-level element <HdlConfig> and child <device> elements
- For devices mentioned in the HDL Platform OHPD, the device element simply has a "name" attribute indicating which of the platform's devices that will be instanced in the platform configuration
- Can also specify devices that are on cards plugged into one of the platform's slots using the "card" attribute or "slot" attribute when there are multiple cards plugged in

```
<HdlConfig>  
  <device name='qdac' />  
  <device name='qadc' card='fmcomms_2_3' />  
</HdlConfig>
```

- Execution environment on some platform that will execute workers
- In HDL, the container is the complete design for an entire FPGA, including workers and infrastructure. Described by XML. Typically built inside of an HDL Assembly directory.
 - Container (BitStream) = Platform Configuration + Assembly + Device Worker(s)
- In RCC, the container loads, executes, controls, and moves data to/from RCC workers

```
<HdlContainer Config='cfg_1rx_1tx' Platform='zed'>
  <!-- external-to-FPGA device (worker) to FPGA assembly connections -->
  <Connection External="in_to_asm_rx_path_from_adc" Port="out" Device="data_src_qadc"/>
  <Connection External="out_from_asm_tx_path_to_dac" Port="in" Device="data_sink_qadc" />
  <!-- FPGA assembly to CPU interconnect connections -->
  <Connection External="out_from_asm_rx_path" Interconnect="zynq"/>
  <Connection External="in_to_asm_tx_path" Interconnect="zynq"/>
</HdlContainer>
```

- Auto-generated VHDL which contains information used at execution and early in the process of platform enablement
- UUID
 - Unique identifier of the bitstream used by the framework during execution to confirm that the desired bitstream is loaded
- ROM
 - Compressed XML that describes the bitstream
 - Used for debug or as a part of a platform inspection process

HDL Platform as it Relates to a Project

- A directory that contains files that implement an HDL platform
 - HDL Platform OHPD <HdlPlatform> and VHDL (arch)
 - HDL Platform Configuration XML files <HdlConfig>
 - HDL Device Workers that are unique to the platform (platform/devices/)
 - File specifying vendor-tool build-time options (.ut)
 - Vendor FPGA constraints files are managed at this level
 - Xilinx *.xdc, Altera *.qsf

With

ocpidev:

```
ocpidev create hdl platform my_platform
```

- Create an HDL platform from the top level of a project
- hdl/platforms/my_platform/my_platform.xml - HDL platform OHPD, which provides:
 - HDL Platform Worker's OWD
 - Additional information regarding hardware aspects of the platform
 - XML attributes, e.g. exact FPGA device part number or OS target for embedded platforms

Attribute Name In Project.xml or Library.xml	Override / Augment Platform Library XML	Override/ Augment Platform Library OHPD	Description
SourceFiles	Y	Y	List of additional source files for this worker (VHDL or Verilog)
Libraries	Y	Y	List of primitive libraries built elsewhere. If a name has no slashes, it will follow the HDL Search Path rules
Configurations	Y	N	List of space-separated HDL Platform Configuration XML files
ExportFiles	Y	N	List of space-separated files to include as symbolic-links in the top-level <i>exports/</i>
XmlIncludeDirs	N	N	List of directories elsewhere for searching for XML files
IncludeDirs	Y	Y	List of directories elsewhere for searching for files indicated by “include” directives
ComponentLibraries	Y	Y	List of component libraries to search for workers
OnlyTargets OnlyPlatforms	Y	Y	List of targets/platforms for which worker may be built
ExcludeTargets ExcludePlatforms	Y	Y	List of targets/platforms for which worker may not be built

- Other files to be added by developer
 - <platform>.ut - Xilinx specific build-time global options
 - <platform>.sdc - Altera specific build-time global options
 - <platform>.{xdc|qsf} - Vendor-specific FPGA constraints file

VHDL

- Auto-generated VHDL based on the HDL Platform Worker OHPD XML file
- hdl/platforms/<platform>/gen/<platform>-impl.vhd (auto-gen entity/arch)
 - <platform> (entity/arch of the <platform>-impl.vhd. Wraps the <platform>_rv entity to expand the control interface records into signals which is required for subsequent code-generation processes when building for the Assembly)
 - <platform>_wci (auto-gen entity/arch)
 - <platform>_rv (auto-gen entity/arch "Record VHDL")
 - <platform>_wci (auto-gen instance)
 - <platform>_worker (auto-gen entity)
 - <Your VHDL is written here!>.vhd (auto-gen arch shell for worker)
- <platform>_worker_defs (auto-gen package that defines records for props_in, props_out, ctl_in, ctl_out, and memory map property)
 - DataInterfaces are not supported!

VHDL

- <worker>/gen/<worker>-impl.vhd (auto-gen entity/arch)
 - <worker> (entity/arch of the <worker>-impl.vhd. Wraps the <worker>_rv entity to expand the control, in and out interfaces records into signals which is required for subsequent code-generation processes when building for the Assembly)
 - <worker>_wci (auto-gen entity/arch)
 - <worker>_rv (auto-gen entity/arch "Record VHDL")
 - <worker>_wci (auto-gen instance)
 - <worker>_wsi.slave (auto-gen instance)
 - <worker>_wsi.master (auto-gen instance)
 - <worker>_worker (auto-gen entity)
 - <Your VHDL is written here!>.vhd (auto-gen arch shell for worker)
 - <worker>_worker_defs (auto-gen package that defines records for props_in, props_out, ctl_in, ctl_out, in_in, out_out, and memory map property)

Hierarchy of the FPGA

- Container (Bitstream) = Platform Configuration + Assembly + Device Worker(s)
 - Auto or User-defined XML and auto-generated VHDL
- Platform Configuration(s) = Platform Worker + Time Server + Device Worker(s)
 - User-defined XML and auto-generated VHDL
- Platform Worker = IP Infrastructure HDL code + User-generated + Primitives + Slots
 - User-defined XML and auto-generated and user-generated VHDL
- Assembly = Application Worker(s)
 - User-defined XML and auto-generated VERILOG!
- Application and Device Workers = User-generated + Primitives
 - Auto or User-defined XML and auto-generated and user-generated VHDL
- Primitives
 - User-generated (ideally generic) VHDL, vendor tool generated, 3rd party, IP cores

- Container (Bitstream) = Platform Configuration + Assembly + Device Worker(s)
 - Auto-generated -impl.vhd (entity) and -assy.vhd (arch)
- Platform Configuration(s) = Platform Worker + Time Server + Device Worker(s)
 - Auto-generated -impl.vhd (entity) and -assy.vhd (arch)
- Platform Worker = IP Infrastructure HDL code + User-generated + Primitives + Slots
 - Auto-generated -impl.vhd (entity) and -assy.vhd (arch) shell, with User-generated arch content
- Assembly = Application Worker(s)
 - Auto-generated -impl.vhd (entity) and -assy.v (arch) VERILOG!
- Application and Device Workers = User-generated + Primitives
 - Auto-generated -impl.vhd (entity) and <worker_name>.vhd (arch) shell, with User-generated arch content
- Primitives
 - User-generated (ideally generic) VHDL, vendor tool generated, 3rd party, IP cores