Py2HWSW

Python framework for embedded hardware/software codesign

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1 Introduction

Open-source Python framework for managing files, automating project flows of embedded hardware/software codesign projects, and partially generating Verilog hardware components. The framework simplifies the project structure, addresses challenges in Hardware Design Languages like Verilog and VHDL, and automates emulation, simulation, FPGA, and ASIC flows. The proposed Verilog generator offers flexibility, user control, and ease of use, producing human-readable code compatible across FPGAs and ASICs.

1.1 What Is Py2HWSW?

In the rapidly evolving landscape of hardware design, the need for efficient and flexible tools is paramount. Enter py2hwsw, a powerful tool designed to streamline the process of generating Verilog cores from high-level descriptions provided in Python or JSON dictionaries. With py2hwsw, engineers can easily translate their design specifications into functional hardware components, significantly reducing development time and complexity.

1.2 What Is Py2HWSW For?

Py2HWSW is designed to do the following:

- **Core Generation**: Generates Verilog cores from descriptions in Python or JSON dictionaries.
- **Framework Compatibility**: Integrates seamlessly with existing Verilog cores and frameworks.
- **High-Level Configuration**: Allows configuration of cores via high-level Python parameters.
- **Automated Resources**: Produces scripts and Makefiles for deployment in various FPGAs, simulators, and synthesis tools, along with documentation.
- **Readable Code**: Generates legible Verilog code with comments for better understanding and maintenance.

1.3 What Problem Does Py2HWSW Solve?

Py2hwsw addresses several key challenges in the hardware design process:

- **Complexity of Verilog Coding**: Writing Verilog code can be intricate and error-prone, especially for those who may not be deeply familiar with hardware description languages. Py2hwsw simplifies this by allowing designers to specify their hardware requirements using high-level Python or JSON dictionaries, reducing the need for extensive Verilog knowledge.
- **Integration of Existing Designs**: Many projects involve legacy Verilog cores that need to be integrated with new designs. Py2hwsw facilitates this integration, enabling users to leverage existing components while still benefiting from the tool's advanced features.
- **Configuration Challenges**: Customizing hardware components often requires deep dives into low-level code. Py2hwsw allows for high-level configuration through Python parameters, making it easier for designers to adjust their designs without getting bogged down in the details of Verilog.

- **Resource Generation**: The process of preparing scripts and Makefiles for various deployment environments can be tedious and time-consuming. Py2hwsw automates this process, providing users with the necessary resources to run their designs on different FPGAs, simulators, and synthesis tools.
- **Code Readability and Maintenance**: Maintaining and debugging hardware designs can be challenging, especially when the code is not well-documented. Py2hwsw generates legible Verilog code with comments, enhancing readability and making it easier for teams to collaborate and maintain their designs over time.

In summary, Py2hwsw streamlines the hardware design workflow, making it more accessible, efficient, and manageable for engineers and designers.

1.4 What Design Principles Underlie Py2HWSW?

Py2HWSW works by:

- **Standard Py2HWSW syntax**: Use a standard Py2HWSW syntax **??** to describe each core.
- **Support Python dictionaries and JSON files**: Supports Python dictionaries to generate dynamic cores based on python parameters. And supports JSON files to describe fixed cores and for compatibily with cores generated by external tools.
- **Support custom verilog snippets**: Each core may include custom verilog snippets for any edge-case which cannot be described using Py2HWSW syntax.
- **Internal Object-Oriented structure**: Py2HWSW converts core descriptions into its internal object-oriented system, creating high-level abstractions of Verilog building blocks.

1.5 How Does Py2HWSW Accomplish Its Goals?

Py2HWSW does this by:

- **Two-Step Development Process**: The core development is divided into two distinct phases: the **setup** phase and the **build** phase. During the setup phase, Verilog source files are generated based on high-level descriptions provided in Python or JSON format. The build phase then utilizes these Verilog sources to produce the necessary FPGA bitstreams, netlists, and other deployment files.
- **Independent Setup Folders**: Each core is organized within its own independent setup folder, containing high-level description files and, if needed, low-level files as well.
- **Core Description Input**: The core's specifications are provided to Py2hwsw in the form of JSON or a Python dictionary, utilizing standard Py2hwsw attributes.
- **Flexible Attribute Handling**: When generating the cores dictionary via a Python script, users can include a set of standard Py2hwsw attributes alongside their own custom-defined attributes.

Learn more about 3[[How It Works]] and **??**[[How To Use]].

2 Getting Started

2.1 Setup Directory

The setup directory of a core may have the following structure:

```
.
├── core_name.py
├── core_name.json
├── document
│   ├── doc_build.mk
│   ├── figures
│   └── tsrc
├── hardware
│   ├── src
│   ├── fpga
│   │   ├── fpga_build.mk
│   │   ├── src
│   │   ├── quartus
│   │   └── vivado
│   ├── modules
│   ├── simulation
│   │   ├── sim_build.mk
│   │   └── src
│   └── syn
│       ├── src
│       └── genus
├── software
│   ├── sw_build.mk
│   └── src
├── scripts
├── submodules
├── Makefile
├── README.md
├── LICENSE
├── CITATION.cff
└── default.nix
```

Only the `core_name.py` or `core_name.json` file is needed to pass the core's description to Py2HWSW. The remaining directories and files are optional.

If the `document`, `hardware`, and `software` directories exist, they will be copied to the `build` directory, overriding any files already present there, such as standard ones or files from other cores.

The `*_build.mk` files allow the user to include core specific Makefile targets and variables from the build process. These will be copied to the `build` directory and included in the standard build process Makefiles.

The `src` directories contain manually written Verilog/C/TeX sources for the core, should they be needed.

The following directories and files do not follow a mandatory structure, but are typically used for the following purposes:

The `hardware/modules` and `submodules` directories typically contain setup directories of other cores.

The `scripts` directory contains scripts specific to the core, and may be called by the user or from the `core_name.py` script.

A simple example of a core's setup directory is available for the iob_and core.

A more complex example of a core's setup directory is available for the iob_soc core.

2.2 Create An AND Gate Core: iob_and

The simplest core description for Py2HWSW is as follows:

```
# SPDX-FileCopyrightText: 2024 IObundle
#
# SPDX-License-Identifier: MIT


def setup(py_params_dict):
    attributes_dict = {
        "version": "0.1",
        "generate_hw": True,
        "confs": [
            {
                "name": "general",
                "descr": "General group of confs",
                "confs": [
                    {
                        "name": "W",
                        "type": "P",
                        "val": "21",
                        "min": "1",
                        "max": "32",
                        "descr": "IO width",
                    },
                ],
            },
        ],
        "ports": [
            {
                "name": "a_i",
                "descr": "Input port",
                "signals": [
                    {"name": "a_i", "width": "W"},
                ],
            },
            {
                "name": "b_i",
                "descr": "Input port",
                "signals": [
                    {"name": "b_i", "width": "W"},
                ],
            },
```

```
            {
                "name": "y_o",
                "descr": "Output port",
                "signals": [
                    {"name": "y_o", "width": "W"},
                ],
            },
        ],
        "superblocks": [
            {
                "name": "simulation",
                "descr": "Blocks for simulation",
                "blocks": [
                    # Simulation wrapper
                    {
                        "core_name": "iob_sim",
                        "instance_name": "iob_sim",
                        "dest_dir": "hardware/simulation/src",
                    },
                ],
            },
        ],
        "snippets": [{"verilog_code": "   assign y_o = a_i & b_i;"}],
    }

    return attributes_dict
```

View Source

More examples and information can be found in the **??**[[How To Use]] section.

A set of basic cores to showcase the various Py2HWSW features can be found in the basic_tests directory.

2.3 Setup And Build

To checkout the source and setup the example iob_and core:

```
$ git clone --recursive git@github.com:IObundle/py2hwsw.git
$ cd py2hwsw/
$ nix-shell py2hwsw/lib/ # Optional step to install environment with
   necessary dependencies
$ py2hwsw iob_and setup --no_verilog_lint
```

To do a clean setup:

```
$ py2hwsw iob_and clean
$ py2hwsw iob_and setup --no_verilog_lint
```

The setup process will generate a build directory containing the core's verilog sources and build files. By default, the build directory is '../[core_name]_V[core_version]'.

To build and run the core in simulation:


```
$ make -C ../iob_and_V* sim-run
```

3 How It Works

This section gives a detailed description of the Py2HWSW framework.

3.1 Setup Flow Chart

Figure 1 presents a high-level flow chart of the Py2HWSW setup procedure.

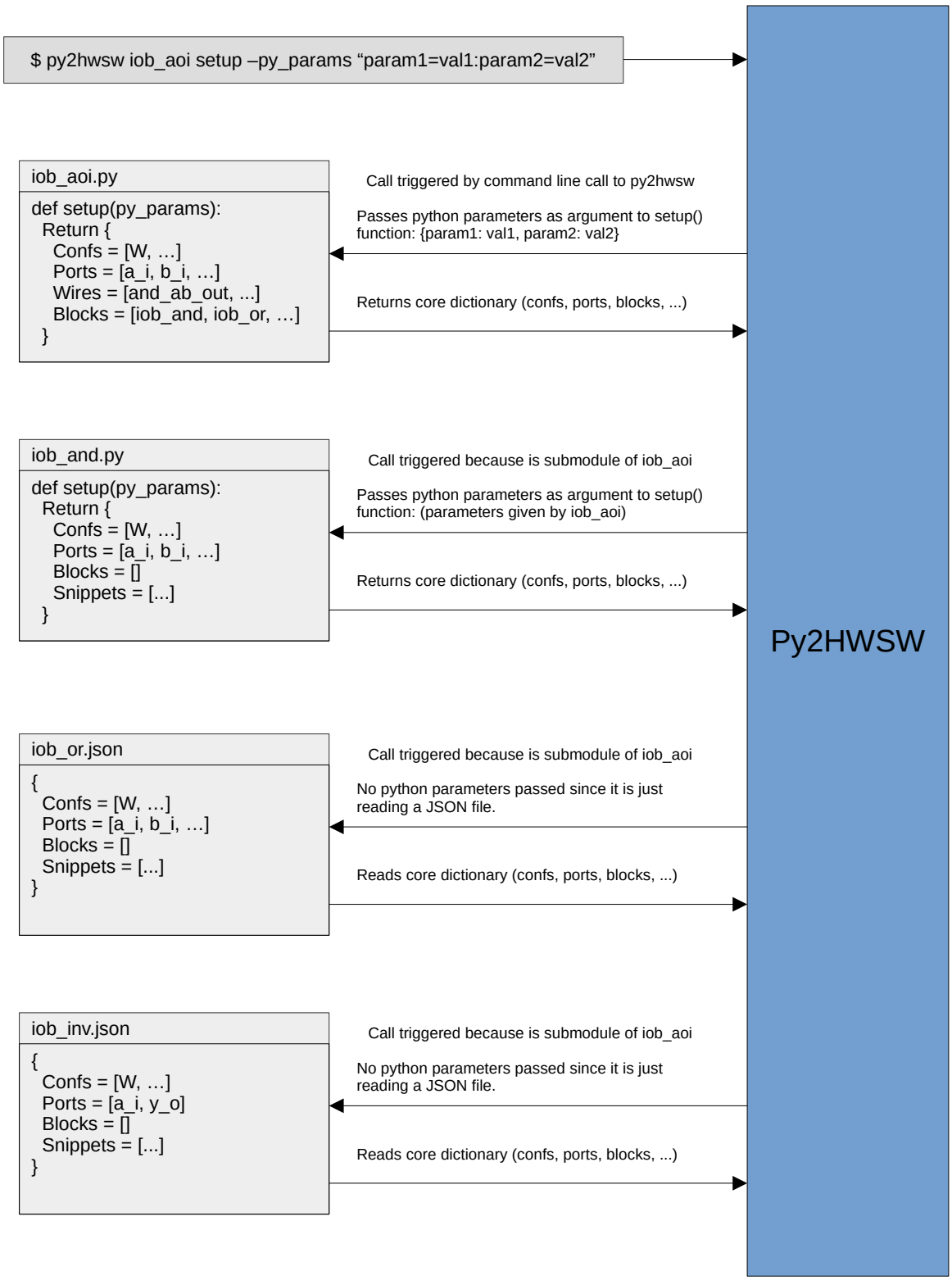

Figure 1: High-Level Flow Chart of Py2HWSW Setup Procedure

3.2 Block hierarchy

Figure 2 presents an example block hierarchy for a Py2HWSW project. Superblocks are only used if they are superblocks of the project's top module or of one of its wrappers.

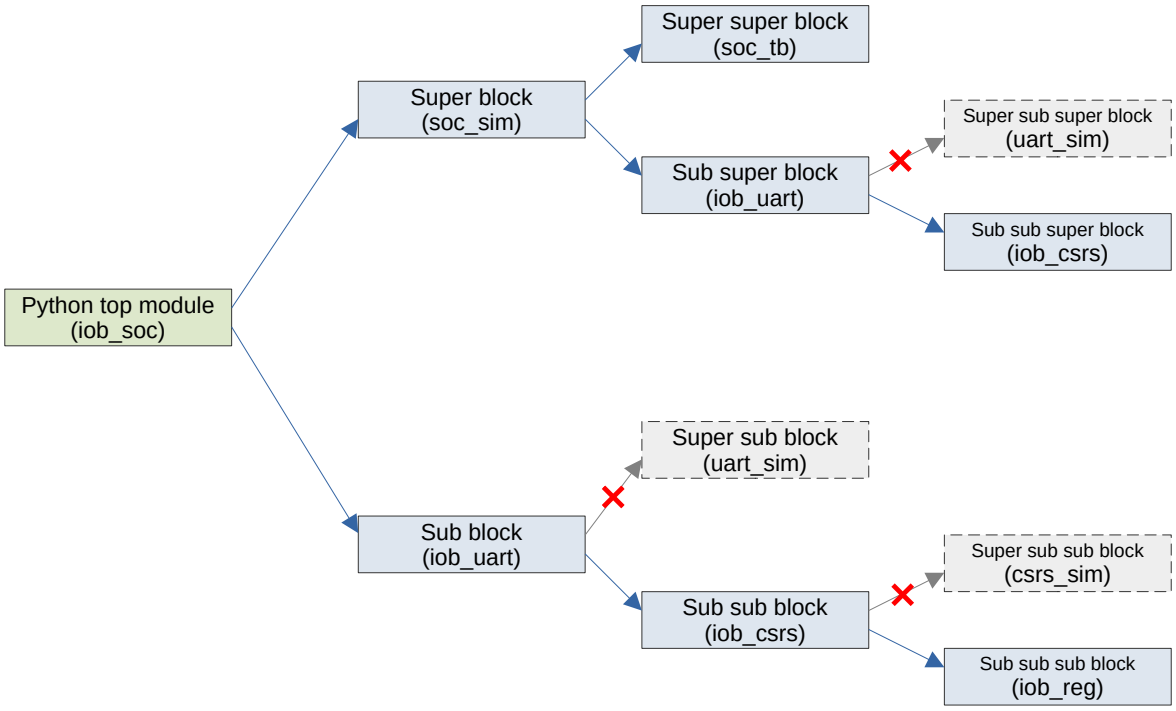

Figure 2: Block Hierarchy of a Py2HWSW Project

3.3 Standard Interfaces

The py2hwsw framework provides the following two standard interfaces: 1) Core "setup" function receives information from py2hwsw via "Python Parameters". 2) Core "setup" function returns a core description to py2hwsw via a python dictionary.

The core's "setup" function is the python function defined by the user in the ¡core_name¿.py file.

If the core is described by a JSON file, then the "Python Parameters" interface is not available. The JSON file gives a dictionary to py2hwsw, similar to the python dictionary of the "setup" function. This allows the user to use external tools to generate cores in JSON format.

3.4 Main launch script: py2hwsw.py

The main launch script for the Py2HWSW progam is the ‘py2hwsw.py‘ script.

The following code snippet from that script processes the command line arguments and launches the program for the specified ”target”.

```
    iob_core.global_build_dir = args.build_dir
    iob_core.global_project_root = args.project_root
    iob_core.global_project_vformat = args.verilog_format
    iob_core.global_project_vlint = args.verilog_lint
    iob_core.global_clang_format_rules_filepath = args.clang_rules
    iob_base.debug_level = args.debug_level

    if args.py2hwsw_docs:
        iob_core.setup_py2_docs(PY2HWSW_VERSION)
        exit(0)

    if not args.core_name:
        parser.print_usage(sys.stderr)
        fail_with_msg("Core name is required.")

    py_params = {}
    if args.py_params:
        for param in args.py_params.split(":"):
            k, v = param.split("=")
            py_params[k] = v

    if args.target == "setup":
        iob_core.get_core_obj(args.core_name, **py_params)
    elif args.target == "clean":
        iob_core.clean_build_dir(args.core_name)
    elif args.target == "print_build_dir":
        iob_core.print_build_dir(args.core_name, **py_params)
    elif args.target == "print_core_dict":
        iob_core.print_core_dict(args.core_name, **py_params)
    elif args.target == "print_py2hwsw_attributes":
        iob_core.print_py2hwsw_attributes(args.core_name, **py_params)
    else:
        fail_with_msg(f"Unknown target: {args.target}")
```

View Source

3.5 Main class for core representation: iob_core.py

The iob_core class is the main class used to represent a core.

It inherits attributes from its parent classes iob_module and iob_instance.

```
class iob_core(iob_module, iob_instance):
```

View Source

The get_core_obj function is used to generate an instance of a core based on a given core name and python parameters. This method will search for the corresponding Python or JSON file of the core, and generate a python object based on info stored in that file, and info passed via python parameters.

```
        """Parse attributes dictionary given, and build and set the corresponding
        attributes for this core, using the handlers stored in `ATTRIBUTE_PROPERTIES`
        dictionary.
        If there is no handler for an attribute then it will raise an error.
        """
        # For each attribute of the dictionary, check if there is a handler,
        # and use it to set the attribute
        for attr_name, attr_value in attributes.items():
            if attr_name in self.ATTRIBUTE_PROPERTIES:
                self.ATTRIBUTE_PROPERTIES[attr_name].set_handler(attr_value)
            else:
                fail_with_msg(
                    f"Unknown attribute '{attr_name}' in core {attributes['original_name']}"
                )

    def lint_and_format(self):
        """Run Linters and Formatters in setup and build directories."""
        # Find Verilog sources and headers from build dir
        verilog_headers = []
        verilog_sources = []
        for path in Path(os.path.join(self.build_dir, "hardware")).rglob("*.vh"):
            # Skip specific Verilog headers
            if path.name.endswith("version.vh") or "test_" in path.name:
                continue
            # Skip synthesis directory # TODO: Support this?
            if "/syn/" in str(path):
                continue
            verilog_headers.append(str(path))
            # print(str(path))
        for path in Path(os.path.join(self.build_dir, "hardware")).rglob("*.v"):
            # Skip synthesis directory # TODO: Support this?
            if "/syn/" in str(path):
                continue
            verilog_sources.append(str(path))
            # print(str(path))

        # Run Verilog linter
        if __class__.global_project_vlint:
            verilog_lint.lint_files(verilog_headers + verilog_sources)

        # Run Verilog formatter
        if __class__.global_project_vformat:
            verilog_format.format_files(
                verilog_headers + verilog_sources,
```

```
                os.path.join(os.path.dirname(__file__), "verible-format.
                    rules"),
            )

        # Run Python formatter
        sw_tools.run_tool("black")
```

View Source

3.6 Configuration class: iob_conf.py

The iob_conf class is used to represent a configuration option of the core. This class contains a set of attributes, each preceded by a comment describing the purpose of the attribute.

```
class iob_conf:
    """Class to represent a configuration option."""

    # Identifier name for the configuration option.
    name: str = ""
    # Type of configuration option, either M (Verilog macro), P (Verilog
        parameter) or F (Verilog false-parameter).
    # False-parameters are the same as verilog parameters except that the
        its value must not be overriden.
    type: str = ""
    # Value of the configuration option.
    val: str | int | bool = ""
    # Minimum value supported by the configuration option (NA if not
        applicable).
    min: str | int = "NA"
    # Maximum value supported by the configuration option (NA if not
        applicable).
    max: str | int = "NA"
    # Description of the configuration option.
    descr: str = "Default description"
    # Only applicable to Verilog macros: Conditionally enable this
        configuration if the specified Verilog macro is defined/undefined.
    if_defined: str = ""
    if_not_defined: str = ""
    # If enabled, configuration option will only appear in documentation.
        Not in the verilog code.
    doc_only: bool = False
```

View Source

The iob_conf_group class is used to represent a group of configuration options. This class contains a set of attributes, each preceded by a comment describing the purpose of the attribute.

```
class iob_conf_group:
    """Class to represent a group of configurations."""

    # Identifier name for the group of configurations.
    name: str = ""
    # Description of the configuration group.
```



```
    descr: str = "Default description"
    # List of configuration objects.
    confs: list = field(default_factory=list)
    # If enabled, configuration group will only appear in documentation. Not
        in the verilog code.
    doc_only: bool = False
    # If enabled, the documentation table for this group will be terminated
       by a TeX '\clearpage' command.
    doc_clearpage: bool = False
```

View Source

The py2hwsw tool uses methods from the config_gen.py script to generate the '*_conf.vh' file, which contains all the Verilog macros that must be held for every design instance of the core.

Each generated Verilog macro is based on the attributes from the corresponding instance of the 'iob_conf' class.

```
    for group in macros:
        # If group has 'doc_only' attribute set to True, skip it
        if group.doc_only:
            continue
        for macro in group.confs:
            # If macro has 'doc_only' attribute set to True, skip it
            if macro.doc_only:
                continue
            if macro.if_defined:
                file2create.write(f"`ifdef {macro.if_defined}\n")
            if macro.if_not_defined:
                file2create.write(f"`ifndef {macro.if_not_defined}\n")
            # Only insert macro if its is not a bool define, and if so only
               insert it if it is true
            if type(macro.val) is not bool:
                m_name = macro.name.upper()
                m_default_val = macro.val
                file2create.write(f"`define {core_prefix}{m_name} {
                   m_default_val}\n")
            elif macro.val:
                m_name = macro.name.upper()
                file2create.write(f"`define {core_prefix}{m_name} 1\n")
            if macro.if_defined or macro.if_not_defined:
                file2create.write("`endif\n")
```

View Source

The py2hwsw tool uses methods from the param_gen.py script to generate the Verilog parameters code that is automatically inserted in the core's Verilog module and instances.

Each generated Verilog parameter is based on the attributes from the corresponding instance of the 'iob_conf' class.

```
    lines = []
    core_prefix = f"{core.name}_".upper()
    for idx, parameter in enumerate(core_parameters):
        # If parameter has 'doc_only' attribute set to True, skip it
```

```
        if parameter.doc_only:
            continue

        p_name = parameter.name.upper()
        p_comment = ""
        if parameter.type == "F":
            p_comment = "  // Don't change this parameter value!"
        lines.append(f"    parameter {p_name} = `{core_prefix}{p_name},{p_comment}\n")

    # Remove comma from last line
    if lines:
        lines[-1] = lines[-1].replace(",", "", 1)
```

View Source

3.7 Signal class: iob_signal.py

The iob_signal class is used to represent a signal for a hardware wire or port. This class contains a set of attributes, each preceded by a comment describing the purpose of the attribute.

```
class iob_signal:
    """Class that represents a wire/port signal"""

    # Identifier name for the signal.
    name: str = ""
    # Number of bits in the signal.
    width: str or int = 1
    # Description of the signal.
    descr: str = "Default description"
    # If enabled, signal will be generated with type `reg` in Verilog.
    isvar: bool = False

    # Used for `iob_comb`: If enabled, iob_comb will infer a register for this signal.
    isreg: bool = False
    # Used for `iob_comb`: List of signals associated to the infered register.
    reg_signals: list[str] = field(default_factory=list)

    # Logic value for future simulation effort using global signals list.
    # See 'TODO' in iob_core.py for more info: https://github.com/IObundle/py2hwsw/blob/a1e2e2ee12ca6e6ad81cc2f8f0f1c1d585aaee73/py2hwsw/scripts/iob_core.py#L251-L259
    value: str or int = 0
```

View Source

The py2hwsw tool uses the `get_verilog_wire`/`get_verilog_port` methods from the `iob_signal` class to generate the Verilog code for the hardware wire/port based on the attributes from the corresponding instance of the `iob_signal` class.

```
    def get_verilog_wire(self):
```



```
        """Generate a verilog wire string from this signal"""
        wire_type = "reg" if self.isvar or self.isreg else "wire"
        width_str = "" if self.get_width_int() == 1 else f"[{self.width
            }-1:0] "
        return f"{wire_type} {width_str}{self.name};\n"
```

```
    def get_verilog_port(self, comma=True):
        """Generate a verilog port string from this signal"""
        self.assert_direction()
        comma_char = "," if comma else ""
        port_type = " reg" if self.isvar or self.isreg else ""
        width_str = "" if self.get_width_int() == 1 else f"[{self.width
            }-1:0] "
        return f"{self.direction}{port_type} {width_str}{self.name}{
            comma_char}\n"
```

View Source

3.8 Wire class: iob_wire.py

The iob_wire class is used to represent a group of hardware wires (signals) used to interconnect components automatically generated. This class contains a set of attributes, each preceded by a comment describing the purpose of the attribute.

```
class iob_wire:
    """Class to represent a wire in an iob module"""

    # Identifier name for the wire.
    name: str = ""
    # Name of the standard interface to auto-generate with `if_gen.py`
        script.
    interface: if_gen.interface = None
    # Description of the wire.
    descr: str = "Default description"
    # Conditionally define this wire if the specified Verilog macro is
        defined/undefined.
    if_defined: str = ""
    if_not_defined: str = ""
    # List of signals belonging to this wire
    # (each signal represents a hardware Verilog wire).
    signals: List = field(default_factory=list)
```

View Source

The ‘signals‘ attribute stores a list of signal objects, represented by the ‘iob_signal‘ class **??**.

The py2hwsw tool uses the ‘generate_wires‘ method from the ‘wire_gen.py‘ script to generate the Verilog code for the wire based on the attributes from the corresponding instance of the ‘iob_wire‘ class.

```
    for wire in core.wires:
        # Open ifdef if conditional interface
        if wire.if_defined:
            code += f"`ifdef {wire.if_defined}\n"
```

```
        if wire.if_not_defined:
            code += f"`ifndef {wire.if_not_defined}\n"

        signals_code = ""
        for signal in wire.signals:
            if isinstance(signal, iob_signal):
                signals_code += "    " + signal.get_verilog_wire()
        if signals_code:
            code += f"    // {wire.name}\n"
            code += signals_code

        # Close ifdef if conditional interface
        if wire.if_defined or wire.if_not_defined:
            code += "`endif\n"
```

View Source

3.9 Port class: iob_port.py

The iob_port class is used to represent an interface for the core. An interface is a group of hardware ports (signals) that may be generic or follow a standard. Due to the similarities between a port and a wire, this class inherits the attributes from the ‘iob_wire‘ **??** class. Besides the inherited attributes, the class contains a set of new port specific attributes, each preceded by a comment describing the purpose of the attribute.

```
class iob_port(iob_wire):
    """Describes an IO port."""

    # External wire that connects this port
    e_connect: iob_wire | None = None
    # Dictionary of bit slices for external connections. Name: signal name; Value: bit slice
    e_connect_bit_slices: list = field(default_factory=list)
    # If enabled, port will only appear in documentation. Not in the verilog code.
    doc_only: bool = False
    # If enabled, the documentation table for this port will be terminated by a TeX '\clearpage' command.
    doc_clearpage: bool = False
```

View Source

Similar to the ‘iob_wire‘ class, the ‘signals‘ attribute stores a list of signal objects, represented by the ‘iob_signal‘ class **??**.

The py2hwsw tool uses the ‘generate_ports‘ method from the ‘io_gen.py‘ script to generate the Verilog code for the port based on the attributes from the corresponding instance of the ‘iob_port‘ class.

```
    for port_idx, port in enumerate(core.ports):
        # If port has 'doc_only' attribute set to True, skip it
        if port.doc_only:
            continue

        # Open ifdef if conditional interface
```



```
        if port.if_defined:
            lines.append(f"`ifdef {port.if_defined}\n")
        if port.if_not_defined:
            lines.append(f"`ifndef {port.if_not_defined}\n")

        lines.append(f"    // {port.name}\n")

        for signal_idx, signal in enumerate(port.signals):
            lines.append("    " + signal.get_verilog_port())

        # Close ifdef if conditional interface
        if port.if_defined or port.if_not_defined:
            lines.append("`endif\n")

    # Remove comma from last port line
    if lines:
        i = -1
        while lines[i].startswith("`endif"):
            i -= 1
        lines[i] = lines[i].replace(",", "", 1)
```

View Source

3.10 Special cases

Most of the cores provived by the py2hwsw's library are built using the standard interfaces mentioned in section 3.3.

However, there are some cores that due to limitations of the standard interfaces, rely instead on internal py2hwsw methods for extra features. The following list describes the cores don't rely solely on the standard interfaces.

- **iob_system**: This core uses the 'is_system' attribute to enable an internal py2hwsw method that automatically fixes the address widths of the cbus interfaces of the system's peripherals.
- **iob_csrs**: The py2hwsw tool contains an internal method to automatically search for the "iob_csrs" subblock and insert a "¡prefix¿_cbus_s" port on the instantiator core of this subblock. It then connects this newly created "¡prefix¿_cbus_s" port of the instantiator core to the iob_csrs "control_if_s" port. The '¡prefix¿' is replaced by instance name of iob_csrs subblock.