POLITECNICO DI MILANO


# M04.2 Bambu: an Open-Source Research Framework for the High-Level Synthesis of Complex Applications.

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# A bit of history about PandA



- PandA framework development started on 2004 as a support research infrastructure for PoliMi in the context of ICODES – FP6-IST EU-funded project
  - Parsing and analysis of TLM 2.0 SystemC descriptions (gcc v.3.5)
- In the hArtes EU-funded project (2006-2010), it was used to
  - Analyzing generic C-based application annotated with pragmas (OpenMP)
  - Extracting parallel tasks
  - Estimating performance of embedded app
  - C-to-C rewriting
- Later, in Synaptic (2009-2013) and in Faster (2011-2014) EU-funded projects, logic- and high-level synthesis has been extended
  - Bambu (HLS tool) was first released in March 2012.
- In these days, the project received further funding to extend its capability and support new targets

# Funding




- The following support is gratefully acknowledged:
  - Xilinx through the donation of two Nexys4 boards and for full licenses of Vivado Design Suite.
  - Altera through the donation of many DE1 CycloneII boards, one DE1-SOC, and a full Quartus software license.
  - NanoXplore through the donation of many licenses of NanoXplore software.
- European Union for funding some of this work through this list of projects:
  - ICODES – Interface and Communication based Design of Embedded Systems
  - hArtes – Holistic Approach to Reconfigurable Real-Time Embedded Systems
  - Synaptic – SYNthesis using Advanced Process Technology Integrated in regular Cells, IPs, architectures, and design platforms
  - Faster – Facilitating Analysis and Synthesis Technologies for Effective Reconfiguration
- European Space Agency for funding some of this work through this list of contracts:
  - ESA/ESTEC/Contract N. 4000100797 – Development of methodologies and tools for predictable, real-time LEON-DSP-based embedded systems.
  - ESA/ESTEC/Contract No. 22167/09/NL/JK. Cache Optimization for LEON Analysis (COLA).
  - ESA/ESTEC/Contract Call-Off Order 4 "Multicore and Schedulability Analysis" for TASTE project.
  - ESA/ESTEC/Contract No. 4000121154/17/NL/LF Compact Reconfigurable Avionics Model-Based Avionic Design (CORA-MBAD)

- Latest funding:
  - HERMES – qualification of High pErformance pRogrammable Microprocessor and dEvelopment of Software ecosystem

    HERMES project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 101004203

  - EVEREST – dEsign enVironmEnt foR Extreme-Scale big data analytics on heterogeneous platforms

    EVEREST project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 957269

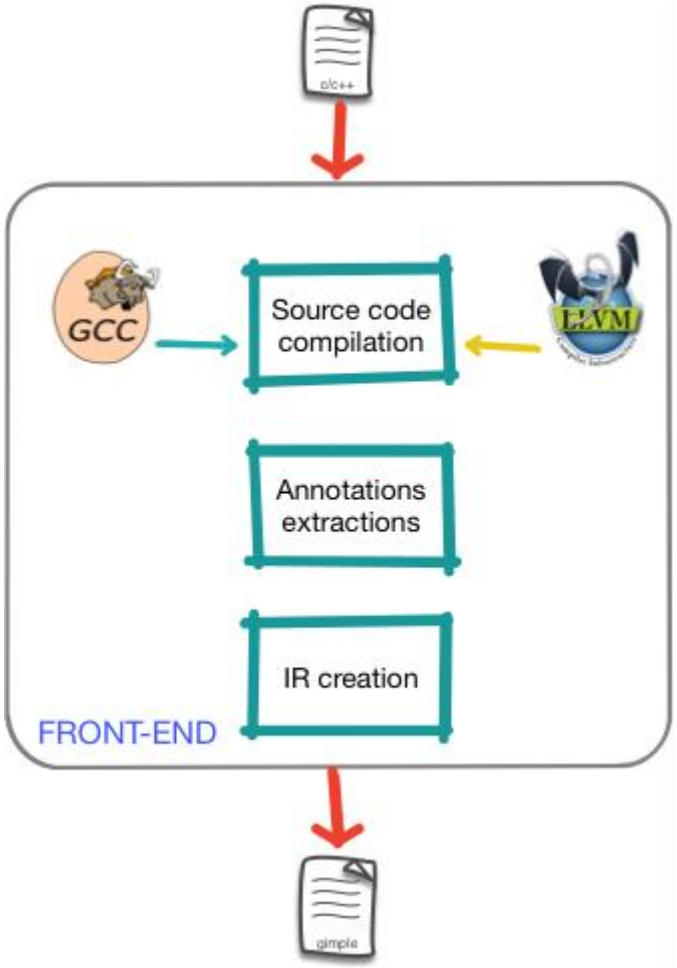
# Bambu: an example of modern HLS tools



- HLS tool developed at Politecnico di Milano (Italy) within the PandA framework
  - Available under GPL v3 at
    - http://panda.deib.polimi.it/
    - https://github.com/ferrandi/PandA-bambu
- Example features
  - Front-end Input: interfacing with GCC/CLANG-LLVM for parsing C code
    - Complete support for ANSI C (except for recursion)
      - Support for pointers, user-defined data types, built-in C functions, etc..
    - Source code optimizations
      - may alias analysis, dead-code elimination, hoisting, loop optimizations, etc...
  - Target-aware synthesis
    - Characterization of the technology library based on target device
  - Verification
    - Integrated testbench generation and simulation
      - automated interaction with Iverilog, Verilator, Xilinx Isim, Xilinx Xsim, Mentor Modelsim
  - Back-end: Automated interaction with commercial synthesis tools
    - FPGA: Xilinx ISE, Xilinx Vivado, Altera Quartus, Lattice Diamond, NanoXplore
    - ASIC: OpenRoand (Nangate 45, ASAP7)

# Bambu: front-end





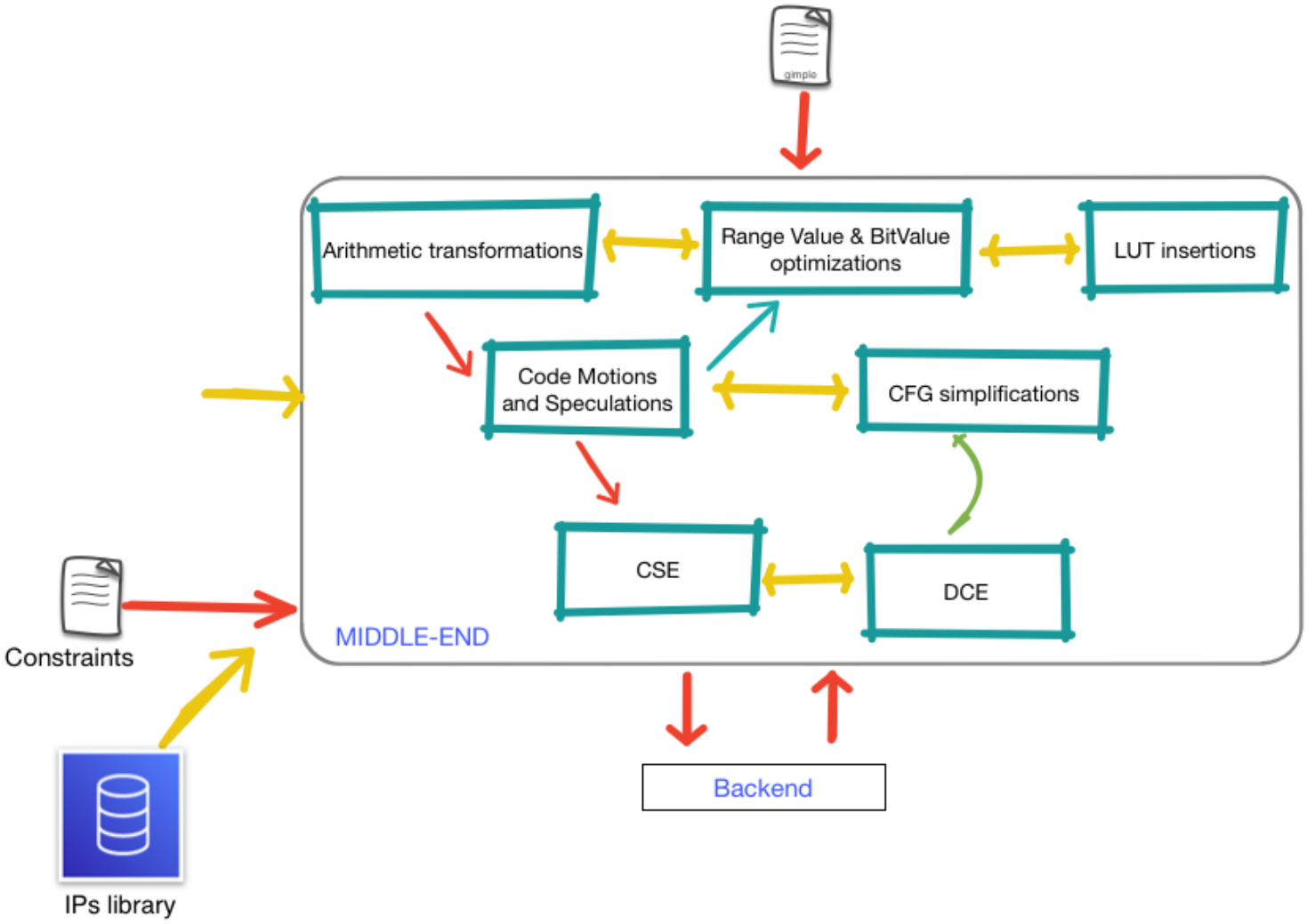
# Bambu IR: behavior



- Gimple-like IR for the beviavior
  - SSA-based, 3 address form, BB, CFG, Call graph
  - Some extensions:
    - Predicated statements
      - Vectorization, Speculation/Code Motion and Tensor Optimizations
    - Code annotations coming from user directives
    - External interfaces with a specific protocol
    - Parallel annotations (OpenMP)
  - Serializable:
    - compressed gimple form (used to store pre-compiled libraries): libm, libc
    - C code that can be compiled (co-simulation)
    - LLVM .ll input supported in case a clang front-end compiler is used
    - MLIR input is supported through LLVM lowering

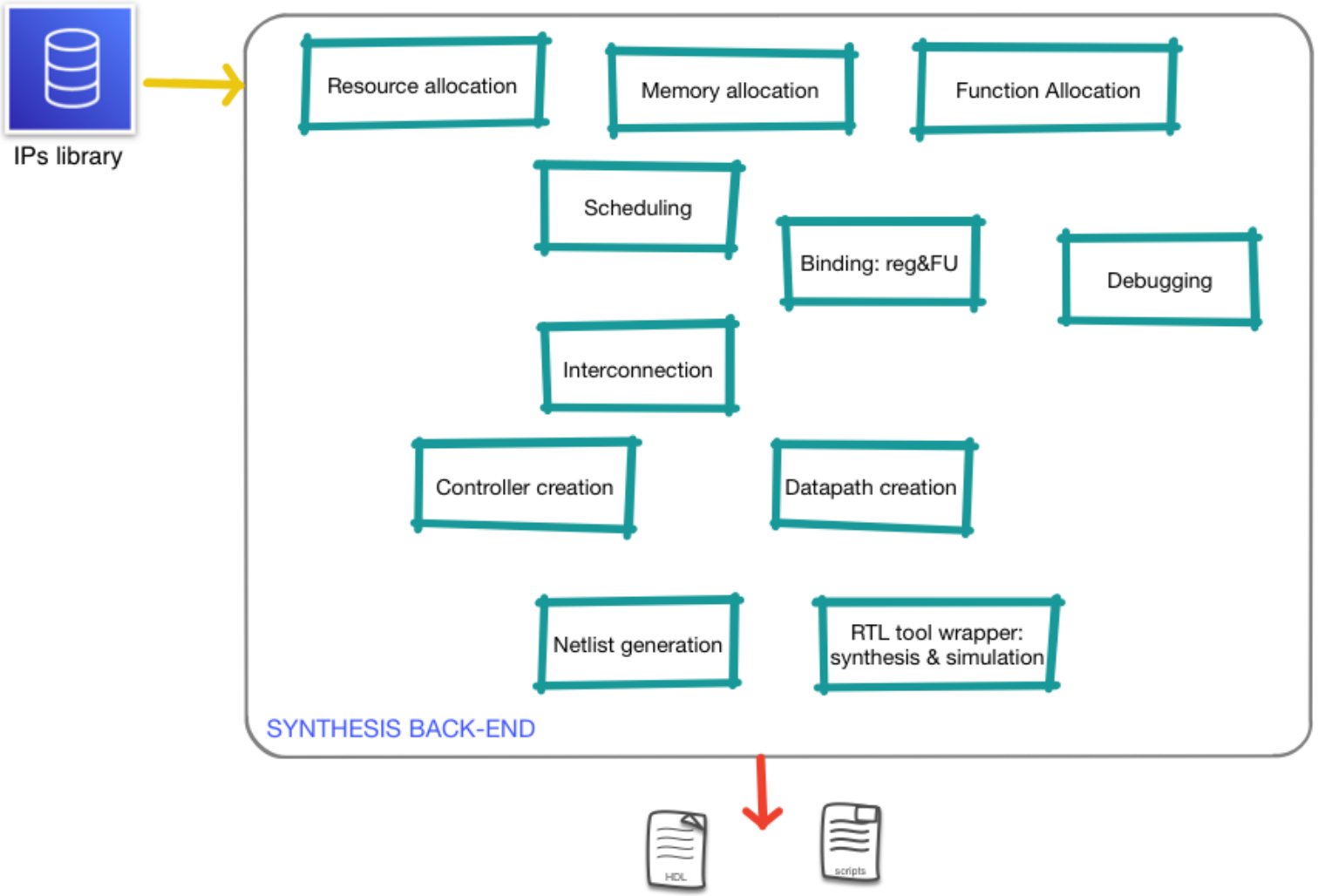
# Bambu: middle-end





# Bambu: back-end





# Bambu IR: circuit



- Circuit for the structure
  - Standard RTL description with: signals, signals_vectors, ports, port_vectors, components
  - Ports and signals are typed
  - Support of global signals (interfaces and proxys)
  - Annotated with area, delay, initiation time, latency
  - Serializabile:
    - Input Functional unit libraries are described in XML format
    - Output in SystemVerilog and VHDL

# Bambu: command-line interface



- Minimal command
  - `$ bambu filename.c`
- Select the top component
  - `$ bambu filename.c -top-fname=top_function_name`
- Controlling the clock period (100Mhz)
  - `$ bambu filename.c --clock-period=10`
- Select the device
  - `$ bambu filename.c -device-name=xc7z020,-1,clg484,VVD`

# Subset of synthesizable C (1)



- We support what standard compilers accept as input (CLANG/LLVM and GCC)
- Supported features:
  - Expressions of any kind: arithmetic, logical, bitwise, relational, conditional, comma-based expressions.
  - Types: integers, single- and double-precision floating point, _Bool and Complex, struct-or-union, bitfields, enum, typedef, pointers and arrays, type qualifiers.
  - Variable declarations, initialization, storage-specifiers
  - Functions definition and declaration, extern or static, pointer to functions, parameters passed by copy or reference, tail recursive functions.
  - Statements and blocks: labeled (case), compound, expression, selection (if,switch), iteration(while,do,for), jump (goto,continue,break,return)
  - All preprocessor directives
  - Unaligned memory accesses and dynamic pointers resolution
  - GCC vectorization

# Subset not supported



- struct returned by copy
- Non-tailing recursive functions


# libbambu

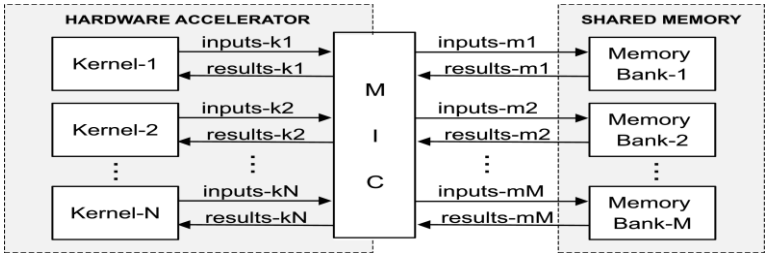


- assert, puts, putchar, read, open, close, write, printf, exit, abort
- libc functions: bswap32,memcmp, memcpy, memmove, memset, malloc, free, memalign, alloca_with_align, calloc, bcopy, bzero, memchr, mempcpy, memrchr, rawmemchr, stpcpy, stpncpy, strcasecmp, strcasestr, strcat, strchr, strchrnul, strcmp, strcpy, strcspn, strdup, strlen, strncasecmp, strncat, strncmp, strncpy, strndup, strnlen, strpbrk, strrchr, strsep, strspn, strstr, strtok
- libm functions: acos, acosh, asin, asinh, atan, atan2, atanh, cbrt, ceil, cexpi, copysign, cos, cosh, drem, erf, exp, exp10, expm1, fabs, fdim, finite, floor, lfloor, fma, fmax, fmin, fmod, fpclassify, frexp, gamma, lgamma, tgamma, hypot, ilogb, infinity, isinf, isnan, j0, j1, jn, ldexp, log, log2, log10, log1p, modf, nan, nearbyint, nextafter, pow, pow10, remainder, remquo, rint, lrint, llrint, round, lround, llround, scalb, scalbln, scalbn, signbit, significand, sin, sincos, sinh, sqrt, tan, tanh, trunc.

# RESEARCH LINES: Parallelization



- architectural template that exploits both instruction level and task-level parallelism
- Dynamic hardware scheduler
- single-cycle hardware context switching
- OpenMP support: omp for, omp simd



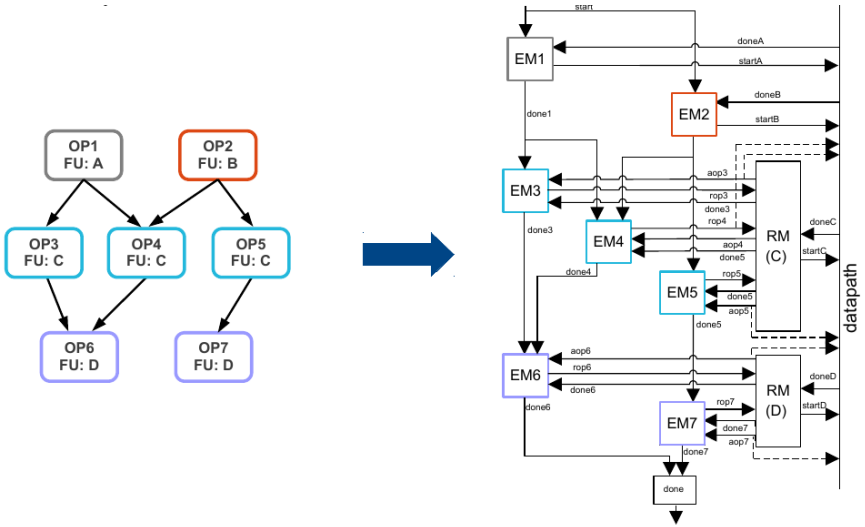


- M. Minutoli, V. G. Castellana, N. Saporetti, S. Devecchi, M. Lattuada, P. Fezzardi, A. Tumeo, and F. Ferrandi, "Svelto: High-Level Synthesis of Multi-Threaded Accelerators for Graph Analytics," *IEEE Transactions on Computers*, vol. 71, iss. 3, pp. 520-533, 2022.
- M. Lattuada and F. Ferrandi, "Exploiting Vectorization in High Level Synthesis of Nested Irregular Loops," Journal of Systems Architecture, vol. 75, pp. 1-14, 2017.
- V. G. Castellana and F. Ferrandi, "An automated flow for the High Level Synthesis of coarse grained parallel applications," in Proceedings of the International Conference on Field-Programmable Technology (FPT), 2013, pp. 294-301.

# RESEARCH LINES: Dynamic vs static scheduling



- FSMD vs adaptive controller
  - Imperative vs dataflow oriented
- Hierarchical memory controller: parallel accesses



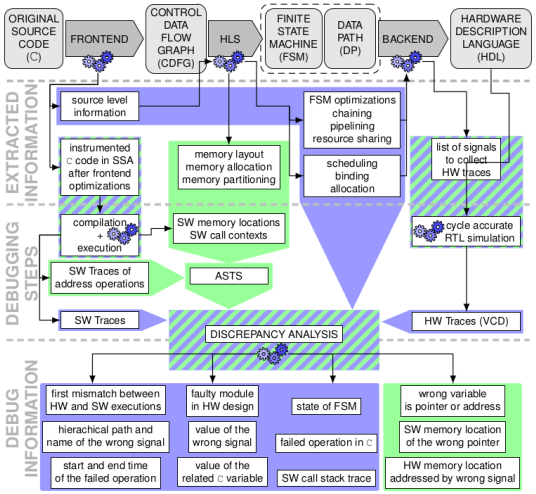


- V. G. Castellana, A. Tumeo, and F. Ferrandi, "High-Level Synthesis of Parallel Specifications Coupling Static and Dynamic Controllers," in *2021 IEEE International Parallel and Distributed Processing Symposium (IPDPS)*, 2021, pp. 192-202.
- V. G. Castellana, A. Tumeo, and F. Ferrandi, "An adaptive Memory Interface Controller for improving bandwidth utilization of hybrid and reconfigurable systems," in Proceedings of the Design, Automation and Test in Europe Conference and Exhibition (DATE), 2014, pp. 1-4.

# RESEARCH LINES: Verification and Debug



- automated technique for bug identification: discrepancy analysis
  - Comparing HLS-generated hardware traces with the software traces

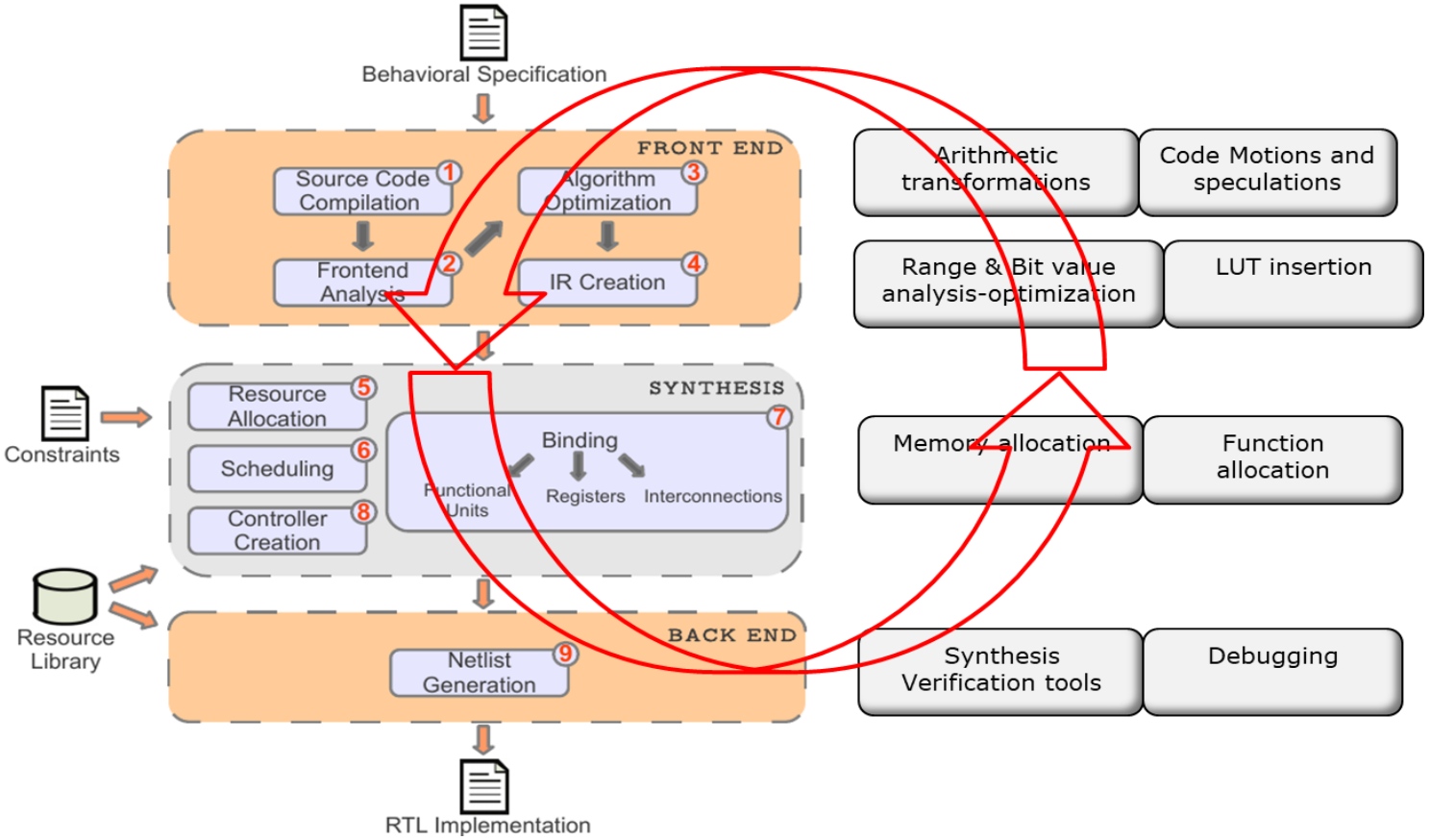




- P. Fezzardi and F. Ferrandi, "Automated Bug Detection for High-Level Synthesis of Multi-Threaded Irregular Applications," *ACM Trans. Parallel Comput.*, vol. 7, iss. 4, 2020.
- P. Fezzardi, M. Lattuada, and F. Ferrandi, "Using Efficient Path Profiling to Optimize Memory Consumption of On-Chip Debugging for High-Level Synthesis," *ACM Transactions on Embedded Computing Systems – Special Issue on ESWEEK2017*, vol. 16, iss. 5s, p. 149:1–149:19, 2017.
- P. Fezzardi and F. Ferrandi, "Automated bug detection for pointers and memory accesses in High-Level Synthesis compilers," in *2016 26th International Conference on Field Programmable Logic and Applications (FPL)*, 2016, pp. 1-9.

# RESEARCH LINES: Design space exploration for HLS

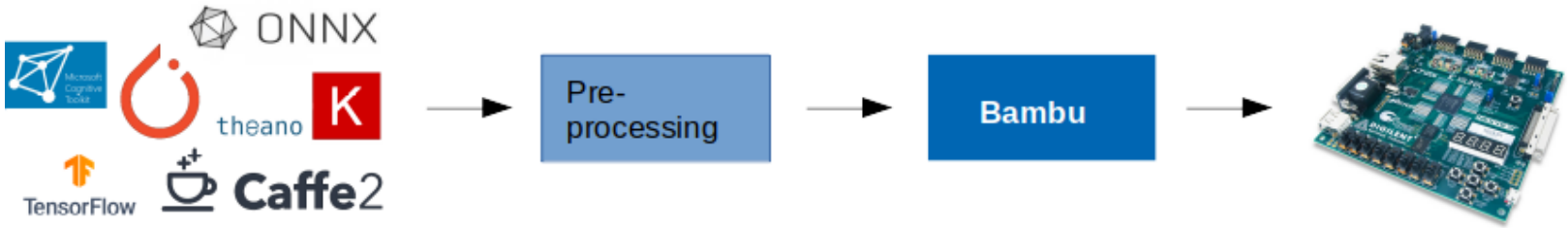





- M. Lattuada and F. Ferrandi, "A Design Flow Engine for the Support of Customized Dynamic High Level Synthesis Flows," ACM Trans. Reconfigurable Technol. Syst., vol. 12, iss. 4, p. 19:1–19:26, 2019.
- M. Lattuada and F. Ferrandi, "Code Transformations Based on Speculative SDC Scheduling," in *Proceedings of the IEEE/ACM International Conference on Computer-Aided Design*, 2015, p. 71–77.

# RESEARCH LINES: Machine Learning accelerators






## hls4ml/FINN produce C++ specific to Vivado HLS and Xilinx FPGAs

- generalize the library so that Bambu can produce efficient designs
- use bambu to target FPGAs from any vendor

## onnx-mlir produces LLVM code for CPU

- direct synthesis may be inefficient
- combine with SODA Synthesizer to make it hardware-oriented

# RESEARCH LINES: MLIR integration



- MLIR dialects -> LLVM dialect -> LLVM IR -> bambu
  - any design written in MLIR can be synthesized
- Integrating CIRCT in the bambu backend
  - take advantage of low-level optimizations
- *Higher-Level* synthesis
  - MLIR as higher level of abstraction
  - apply high-level optimizations (e.g. loop pipelining connected with SODA Synthesizer)


- S. Curzel, S. Jovic, M. Fiorito, A. Tumeo, F. Ferrandi, "Higher-Level Synthesis: experimenting with MLIR polyhedral representations for accelerator design", Impact 22.
- S. Curzel, N. B. Agostini, S. Song, I. Dagli, A. Limaye, C. Tan, M. Minutoli, V. G. Castellana, V. Amatya, J. Manzano, A. Das, F. Ferrandi, and A. Tumeo, "Automated Generation of Integrated Digital and Spiking Neuromorphic Machine Learning Accelerators," in *Proceedings of the 40th International Conference on Computer-Aided Design*, New York, NY, USA, 2021.
- M. Siracusa and F. Ferrandi, "Tensor Optimization for High-Level Synthesis Design Flows," *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, Best Paper Candidate of CODES+ISSS 2020*, vol. 39, iss. 11, pp. 4217-4228, 2020.

# Binary distribution now available



- The code is available as AppImage on https://panda.dei.polimi.it
  - bambu-x86_64.AppImage
  - AppImage is a format for distributing portable software on Linux without needing superuser permissions to install the application.
  - Once downloaded just add the execution rights with this command:

```
chmod +x bambu-x86_64.AppImage
```

  - Source code is available on GitHub:
    - https://github.com/ferrandi/PandA-bambu/

# Questions?



http://panda.deib.polimi.it

F. Ferrandi, V. G. Castellana, S. Curzel, P. Fezzardi, M. Fiorito, M. Lattuada, M. Minutoli, C. Pilato, and A. Tumeo, "Invited: Bambu: an Open-Source Research Framework for the High-Level Synthesis of Complex Applications," in 2021 58th ACM/IEEE Design Automation Conference (DAC), 2021, pp. 1327-1330.