Autogenerating Fast Packet-Processing Code Using Program Synthesis

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ABSTRACT
Packet-processing code should be fast. But, it is hard to write fast code for programmable substrates such as high-speed switches, multicore SoC SmartNICs, FPGAs, middleboxes, and the end-host stack. Today, expert developers with deep familiarity with the underlying hardware handcraft such code. Making things worse, building optimizing compilers for these substrates requires significant development effort, which may not be available for these new, niche, and evolving substrates.

We propose an alternative: to automatically generate fast packet-processing code using program synthesis. For the domain of packet processing, using synthesis can generate faster code than an optimizing compiler at the cost of increased compile time. As a case study, we apply program synthesis to build a code generator, Chipmunk, for a simulator of the protocol-independent switch architecture (PISA). Chipmunk generates code for many programs that a previous code generator based on classical compiler optimizations rejects, and code generated by Chipmunk uses much fewer hardware resources. We also outline future directions in applying program synthesis to code generation for packet processing.

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1 INTRODUCTION
There has been a proliferation of programmable network substrates recently. Examples include high-speed programmable switches, multicore SoC SmartNICs, FPGAs, software middleboxes, and the networking stack within servers. With growing link speeds, there is a need to run ever faster packet-processing code on these substrates. For example, SmartNICs run at line rates of 40–100 Gbit/s. Switches run at 100 Gbit/s per port and a few Tbit/s in aggregate.

Although these substrates are programmable, developing fast programs for them is hard for two reasons. First, developing such fast programs requires manual optimization by experts who are familiar with each underlying hardware architecture. These experts must be aware of the cache and memory hierarchy for CPUs and SoC-based NICs; of ALU, TCAM, and SRAM limits for programmable switches; and of lookup tables, placement, and routing for an FPGA. For instance, Microsoft hired a dedicated team of hardware engineers to program its FPGA-based SmartNIC [36]. Second, optimizing compilers might alleviate the difficulties of generating fast code, building optimizing compilers for a target requires significant engineering effort spanning decades [48]—effort that may not be available for new, niche, and evolving network hardware.

In response to the above concerns, we propose the use of program synthesis to develop code generators for emerging network substrates. Program synthesis is the process of automatically generating a program that meets a given specification. We focus on a recent variant of program synthesis called syntax-guided synthesis (SyGuS) [25, 57, 64] that constrains the search space of

Figure 1: Syntax-guided synthesis in SKETCH. ??(b) is a hole whose value is in [0, 2^b – 1]. << is the left-shift operator.
programs using syntactic restrictions. As a concrete example of syntax-guided synthesis, in SKETCH [17, 59], a programmer provides a program synthesizer the specification along with a sketch (Figure 1): a partial program with holes representing values within a finite range of integers. The partial program constrains the search space syntactically and encodes the programmer’s insight into the structure of the implementation. The synthesizer completes the sketch by filling in all holes with concrete values so that the completed sketch meets the specification—or says that synthesis is infeasible.

Syntax-guided synthesis can be applied to code generation by (1) using the developer’s program, say in C or P4, as the specification, (2) using the sketch to represent the structure of the substrate, and (3) using holes to represent a large but finite number of low-level hardware configurations such as assembly opcodes, operand choices for instructions, and contents of look-up tables. Resource constraints can be incorporated by limiting the number of sketch holes and using assertions over the holes. For instance, a switch pipeline with a fixed set of ALUs in each stage can be viewed as a sketch with holes representing hardware configurations such as choices of ALU opcodes and immediate operands (Appendix A). Further, the number of holes in the sketch are limited to reflect physical resource constraints on the number of ALUs and stages in the pipeline.

For fast packet processing, there is value to generating machine code that is near-optimal on some metric (e.g., throughput or latency). Synthesis-based code generators are much better at finding such near-optimal code relative to traditional optimizing compilers. This is because an optimizing compiler’s algorithms are designed to generate consistently good code for all programs within a reasonable compilation time budget; however, synthesis can discover much better code by performing exhaustive search for a longer time. For instance, synthesis techniques have produced x86 and ARM binaries that outperform gcc –03 on programs that are a few hundred instructions long [47, 51]. The price of near-optimal code is increased compile time—a price worth paying for fast packet processing.

Additionally, synthesis might permit rapid prototyping of compilers. This is because synthesis allows us to declaratively specify code generation for different substrates as synthesis problems, e.g., using sketches. This could allow us to reuse synthesis technology for performing code generation across many different packet-processing substrates.

Despite these potential benefits over optimizing compilers, syntax-guided synthesis faces a key challenge: it is a search problem over a large combinatorial search space of programs. The space grows exponentially with the number of bits in the hardware configurations (i.e., the number of bits in the SKETCH holes). However, we believe that our vision is feasible for three reasons. First, after over a decade of research, there are now mature open-source synthesis tools [59, 64] and promising real-world applications of synthesis [23, 38, 46, 51, 53]. Second, several fast packet-processing programs are naturally small (e.g., BLUE [35], RED [37], or RCP [63]) and simple (e.g., no pointers or loops in P4 [31]). This makes synthesis more tractable. Third, many hardware substrates exhibit significant symmetry. This allows us to prune the search space for synthesis by considering only one exemplar hardware configuration out of many equivalent configurations (§3; Figure 4).

We present a case study of applying program synthesis to code generation for packet-processing switch pipelines based on the protocol-independent switch architecture (PISA) [15] (§2.2). The compilation of packet-processing programs to such switch pipelines has an all or nothing flavor [56]: programs that are compiled successfully run at line rate; all other programs fail to compile. Unlike x86 software, there is no graceful degradation of program performance with complexity. Hence, in practice, it can be a complex process to write a program to “fit” into the underlying switch hardware. Compounding this, existing switch compilers [11, 56] routinely reject a program even when a semantically-equivalent rewrite of the program can be compiled, pushing the burden of finding such a rewrite onto the developer.

We design Chipmunk (§3), a synthesis-aided code generator, to generate low-level code for a PISA hardware simulator. We compare Chipmunk with Domino [56] (§4). Chipmunk generates pipelined implementations of many programs that Domino rejects. This is because Domino incorrectly decides that the programs are too expressive to fit into the switch’s computational capabilities. For programs that both Domino and Chipmunk can generate code for, code generated by Chipmunk has much smaller pipeline depth.

We also outline directions for future work in applying program synthesis to generating fast packet processing code (§5). We describe three applications: optimizing packet processing on processors, automatically approximating programs to run faster, and providing performance troubleshooting hints to developers.

2 BACKGROUND

We now overview the programming language we use to program packet-processing pipelines, the hardware architecture of these pipelines, and the program synthesis technology that we use as a building block.

2.1 Programming language

Several languages now exist for packet processing, e.g., P4-14 [19] P4-16 [12], POF [60], NPL [10], and
Figure 2: Chipmunk compilation to a 2-by-2 PISA grid. Wires into input, output muxes elided for clarity.

Table 1: PISA hardware configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALU opcode</td>
<td>ALU’s operation (e.g., add, sub)</td>
</tr>
<tr>
<td>Input mux control</td>
<td>Choice of ALU’s input</td>
</tr>
<tr>
<td>Output mux control</td>
<td>Where a container’s value comes from</td>
</tr>
<tr>
<td>Packet field allocation</td>
<td>The container a packet field occupies</td>
</tr>
<tr>
<td>State variable allocation</td>
<td>The ALU a state variable occupies</td>
</tr>
<tr>
<td>Immediate operands</td>
<td>Constant operands for instructions</td>
</tr>
</tbody>
</table>

2.2 Hardware architecture

We consider a packet-processing pipeline based on the hardware architecture described in RMT [32] and Banzai [56]. RMT provides a hardware architecture for programmable match-action processing, while Banzai extends RMT with stateful computation. The hardware architecture described in RMT and Banzai is commonly known as the Protocol Independent Switch Architecture (PISA) [15] and is the dominant architecture for high-speed programmable switches today [6, 14].

We simulate a simplified form of PISA by abstracting out all switch computation into a 2D grid of ALUs that process all packets (Figure 2). The x axis of this grid represents pipeline stages; the y axis represents parallel ALUs within a pipeline stage. Packets enter the grid from the left and exit from the right, and the grid is assumed to support a throughput of 1 packet per clock cycle, i.e., the line rate of the switching ASIC. A program’s packet fields are stored in the packet header vector (PHV). The PHV is a set of containers. Each container can be thought of as memory that holds a packet field (e.g., pkt.sample in Figure 2) as it is passed and transformed between stages. Similarly, a program’s state variables (e.g., count in Figure 2) are stored within stateful ALUs.

ALUs are PISA’s computation units and can modify either packet fields alone (stateless ALUs) or both fields and switch state (stateful ALUs). Their computations are atomic in that any update to state within an ALU is visible to the next packet arriving at that ALU a clock cycle later. Our simulator allows us to experiment with a variety of simulated switch hardware by specifying different stateful and stateless ALUs with different sets of operations, represented by ALU opcodes. Operands to stateless and stateful ALUs can be PHV containers, immediate operands, or switch state; this choice is determined by an input mux (Figure 2). A stateless ALU’s output is written into the PHV container designated for that stateless ALU. A stateful ALU’s output can be routed into any container; this choice is determined by an output mux. Table 1 summarizes the hardware configurations in our simulator. These are the configurations that need to be populated by any code generator, whether based on classical compiler optimizations or program synthesis.

2.3 Program synthesis using SKETCH

We use the SKETCH program synthesizer for developing Chipmunk. We briefly describe SKETCH’s internals here; [57] has more details. SKETCH is given as inputs a specification to satisfy and a partial program (the sketch) (Figure 1). We consider both the specification and the
null
the allocation constraints, which are expressed as SKETCH assertions. Currently, Chipmunk assigns one packet field to one fixed container over the entire pipeline, limiting the total number of packet fields in the program to at most the number of containers, and excluding the possibility of reusing the same container to store different packet fields in different pipeline stages. We plan to address this restriction in future work.

We can reduce the number of indicator variables and speed up synthesis by exploiting symmetry in the common case of homogeneous grids, where the same stateful and stateless ALU types are repeated across the 2D grid, and each ALU can access the same set of operands using its input muxes. To exploit symmetry, we apply the idea of canonicalization [27] and rename program fields to a canonical set \( f_1, f_2, \ldots, f_m \). We then map \( f_i \) to container 1, \( f_j \) to container 2, etc. Intuitively, any allocation can be changed into a canonicalized one by renumbering containers (Figure 4); hence there is no loss of expressiveness by forcing a canonical allocation.

Allocating state variables to stateful ALUs. State variables from the input specification should be assigned to specific stateful ALUs in the hardware. The indicator variable holes \( I[s, x, y] \) track if state variable \( s \) is assigned to stateful ALU \( x \) in stage \( y \). Similar to allocating packet fields, we exploit symmetry in homogeneous grids, and canonicalize the state variables in the program to \( s_1, s_2, \ldots, s_n \). Hence, variable \( s_i \) is allocated to stateful ALU \( i \) within a stage. However, there is an important wrinkle: SKETCH still needs to determine which stage a state variable \( s_i \) must be allocated to, due to dependencies between state variables, i.e., if an update to state variable \( s_i \) depends on the value of \( s_j \), \( s_j \) must be allocated to a stage that is earlier than that of \( s_i \).

Allocating opcodes and mux controls for ALUs. We use SKETCH holes to represent the opcode used by each ALU and the mux controls. The size of opcode holes depends on the number of operations supported by an ALU. The size of mux holes depends on the number of PHV containers (the pipeline width). In experiments, we find that constraining opcode holes to take on fewer values than the hardware allows can sometimes speed up synthesis (e.g., by only considering arithmetic ALU opcodes), provided the program can be fully expressed using those opcodes. However, at other times, such constraints increase synthesis time if the program requires the full expressiveness of the hardware, causing synthesis to fail. We are designing heuristics to balance both possibilities.

Scaling Chipmunk to a large number of input bits. Once Chipmunk sets up the sketch to synthesize hardware configurations (Table 1), SKETCH’s problem can be stated as: find an assignment of values to all holes so that the sketch and the specification have the same output (new switch state and new packet) for all possible inputs (initial values of switch state and the old packet).

To solve this problem, SKETCH uses the CEGIS algorithm described earlier. However, SKETCH limits the range of inputs to speed up synthesis. By default, SKETCH only searches over all 5-bit integers for each scalar input. Hence, it is possible that the hole assignment returned by SKETCH fails to work over larger input ranges, say 32-bit packet fields. To scale SKETCH to larger input ranges, we decouple the input ranges for synthesis and verification (an idea proposed in prior work [24, 39]) and use a theorem prover to scale verification to much larger input ranges. Specifically, we implement our own “outer-loop” version of CEGIS with SKETCH as the inner synthesis component: we first use SKETCH to find hole assignments over a small input range, and then use the Z3 theorem prover [20] to verify that these assignments are correct for all inputs over a larger range (currently 10-bit integers). If Z3 finds a counterexample, we rerun SKETCH by using the counterexample as an additional concrete input on which the specification and sketch must agree, in addition to SKETCH’s own small input range.

Limitations. First, Chipmunk’s support for immediate ALU operands is preliminary because SKETCH cannot synthesize large constants quickly. Hence, we restrict the size of immediate operands; we plan to fix this by leveraging theory-based constant synthesis proposed in recent work [22]. Second, running Chipmunk on a real switch such as Tofino [14] requires translating Chipmunk’s holes to low-level switch configurations that can be accepted by the Tofino compiler. We are currently designing such a translator.

4 EVALUATION

We compare Chipmunk against the current Domino code generator [56]. The Domino code generator is based largely on classical compiler techniques that use rewrite rules on the abstract syntax tree of the program, e.g., branch elimination and data flow analysis. For benchmarks, we pick a set of test programs drawn from several sources [45, 55, 56]. We then generate code using both Domino and Chipmunk. For a given program and code generator, we measured code generation quality using two metrics: (1) whether the code generator can actually generate code for the program and (2) if it can, the number of stages and the maximum number of ALUs per stage used by the generated code.

Test programs and ALUs. We started with 8 programs drawn from multiple sources [45, 55, 56]. Because these programs were previously compiled with Domino, they

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Footnote:

1Domino does use synthesis in a limited form after much preprocessing, but for engineering expediency rather than for code optimization.
Table 2: Code generation rate and time for Chipmunk and Domino

<table>
<thead>
<tr>
<th>Programs</th>
<th>Chipmunk</th>
<th>Domino</th>
<th>Chipmunk time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCP [63]</td>
<td>100%</td>
<td>100%</td>
<td>17.7</td>
</tr>
<tr>
<td>Stateful Firewall [26]</td>
<td>100%</td>
<td>90%</td>
<td>2295</td>
</tr>
<tr>
<td>Sampling [56]</td>
<td>100%</td>
<td>0%</td>
<td>7.3</td>
</tr>
<tr>
<td>BLUE (increase) [35]</td>
<td>100%</td>
<td>0%</td>
<td>52.5</td>
</tr>
<tr>
<td>BLUE (decrease) [35]</td>
<td>100%</td>
<td>0%</td>
<td>52.5</td>
</tr>
<tr>
<td>Flowlet switching [54]</td>
<td>70%</td>
<td>100%</td>
<td>3648</td>
</tr>
<tr>
<td>Detecting new flows [45]</td>
<td>100%</td>
<td>0%</td>
<td>7.7</td>
</tr>
<tr>
<td>Detecting flow reordering [45]</td>
<td>100%</td>
<td>0%</td>
<td>8.3</td>
</tr>
</tbody>
</table>

Table 2: Code generation rate and time for Chipmunk and Domino

were written to ensure successful code generation with Domino. Hence, to compare Domino and Chipmunk, we mutated these programs in semantic-preserving ways to generate 10 mutations of each of the 8 programs. In theory, both Domino and Chipmunk should be able to successfully generate code for all these mutations because Domino could generate code for the original 8 programs. For each of the mutations, we used the stateful ALU that was used to generate code for the original program. For the stateless ALU, we developed a stateless ALU based on Banzai’s stateless ALU [56], which supports arithmetic, boolean, relational, and conditional operators, similar to RMT.

Results. We supply the 8 * 10 = 80 mutations to both Domino and Chipmunk. We report the fraction of the mutations of each of the 8 original programs that Domino and Chipmunk can successfully generate code for (Table 2). On this metric, Chipmunk is significantly better. Domino fails to generate code for most mutations of the original programs because it incorrectly concludes that the programs are too expressive to be implemented using the pipeline’s ALUs. Chipmunk’s code generation rate is close to 100%. This is expected because Domino can generate code for the original programs; hence, in theory we should be able to generate code for any semantic-preserving mutations of the originals. In one case (flowlet switching), Chipmunk does not successfully generate code for all mutations. This was because Chipmunk’s code generation times are variable and sometimes exceeded our timeout (Table 2). Increasing our timeout causes Chipmunk to successfully generate code for several failed programs.

When both Domino and Chipmunk are successful, we find that Chipmunk significantly reduces the number of pipeline stages required to fit the program (Figure 5). Such improvements are significant because programmable hardware pipelines are severely constrained on the number of pipeline stages, e.g., Tofino has 12 stages [2]. Chipmunk’s output is comparable to and sometimes worse than Domino on the maximum number of ALUs per stage, which is more abundant (e.g., RMT has around 200 per stage [32]). Domino’s resource usage also has more variability across mutations (shown by the error bars) than Chipmunk, which has no variability. Chipmunk’s main drawback relative to Domino (which generates code in a few seconds) is higher and more variable code generation time (Table 2).

5 FUTURE WORK

5.1 Synthesizing Fast Processor Code

Several processor-based2 packet-processing substrates have emerged just in the last few years, such as the eXpress Data Path (XDP [21]), DPDK [5], and SoC-based SmartNICs [7, 9]. On these substrates, it is desirable for programs to run with the highest throughput (i.e., NIC line rate) and least packet-processing latency possible. However, it is challenging to tune performance, since it depends on complex factors such as the layout of data structures, memory access patterns, and low-level assembly instructions emitted by compilers.

Program synthesis in the form of superoptimizing compilation [27, 41, 46, 47, 51] has the potential to better this situation. Unlike a standard optimizing compiler that performs local program transformations to improve performance, a superoptimizing compiler searches over the space of instruction sequences to attempt to find an optimal sequence of instructions (according to a stated objective function such as minimum instruction count) implementing the entire input program. The main caveat is that input programs today are restricted to at most a few hundred instructions; on such programs, superoptimizing compilers have been reported to produce code with performance that beats gcc -O3 output [47, 51].

Research Questions. Existing superoptimizing compilers use very simple performance models (e.g., number of instructions) to optimize programs running on one processor core. Yet, they take significant amounts of time to emit code. Can we enhance superoptimizers to generate code that runs on multi-core SmartNIC platforms? Can we effectively incorporate memory access costs, patterns, and data layouts? Can compilation scale

2We include both multicore SoC SmartNICs and end hosts.
to reasonable-size network programs and run within a reasonable time? Can we formulate an intermediate representation like LLVM to support multiple SmartNIC ISAs for superoptimization?

5.2 Approximate Program Synthesis
There are many situations where data plane resources are heavily constrained, necessitating approximate—but fast—packet processing. Examples include sampled statistics, measurement sketches that trade off counter accuracy for line-rate performance and reduced memory, and multi-tenant scenarios where it is essential to pack as many network programs as possible into the switch or NIC [44]. Each such situation today requires developing a custom approach to trade accuracy for resource savings or high performance.

Program synthesis can provide a general method to reduce program resource usage through approximation. Approximate compilers [34, 43, 50, 52] already exist to target hardware with instructions that reduce energy. Recently, a more general approximate program synthesis framework [29, 30] has emerged. This framework has been used to improve the performance of some programs by an order of magnitude [29] while producing approximate results with bounded errors.

Research Questions. Network programs are typically written as functions over a single packet, e.g., in P4. How should one synthesize network programs with bounded inaccuracy over a packet trace, rather than just a single packet? How should we address resource constraints like memory usage, which depends on the workload (e.g., number of flows) and not just the program? Given a library of high-performance primitives such as counting, hashing, etc., is it possible to synthesize measurement sketches (e.g., count-min sketch) that capture a statistic with guaranteed memory-accuracy tradeoffs?

5.3 Synthesizing Program Repairs
Developers of packet processing programs frequently need to troubleshoot correctness, security, and performance issues with their software. While it is impossible to remove the need for human insight from troubleshooting, we believe it is beneficial to generate human-interpretable repair hints automatically. Yet, there are few avenues today to provide such hints to ease the troubleshooting process.

Small, localized rewrites of the program source code can serve as useful hints to fix many issues. Examples include suggesting edits to a program to fit it into a switch pipeline, rewrites for offending eBPF program code to move past eBPF verification errors [1, 18], and hints to rewrite “hot” code regions of a DPDK program to improve its performance.

Research Questions. Is it possible to generate local rewrites to fit a problematic network program into a packet-processing pipeline? Can we speed up a slow network program by replacing hot code regions with fast implementations using a database of localized code rewrites [27]? Can program synthesis replace unsafe data flows in an eBPF program with safe ones without drastically changing the whole program? It may often be necessary to change the semantics of a program to fix an issue. Can we develop a domain-specific measure of the semantic distance between the rewritten program and the original one? How should a synthesizer use such a measure when suggesting rewrites?

6 RELATED WORK
Program synthesis has been applied to several areas of networking: synthesis of network updates [42, 49], synthesis of routing table configurations from policies [33, 61], the inverse problem of synthesis of policies from configuration [28], and synthesis of control planes [62]. These efforts target synthesis of network-wide policies and configurations, where the policies and configurations pertain to reachability, isolation, and access control. We apply program synthesis to the problem of generating per-device low-level hardware-specific code (e.g., assembly, Verilog, microcode, or FPGA bitstreams) from higher level imperative specifications of packet-processing algorithms.

7 CONCLUSION
Writing fast packet-processing code for programmable network substrates is challenging, and today is best left to experts who deeply understand the underlying hardware. Instead, we propose the use of program synthesis to automatically generate fast packet-processing code. Our initial results are very encouraging. We hope they prompt further research on synthesis-based code generators for programmable network substrates.

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REFERENCES
an-ebpf-overview-part-1-introduction/.


A APPENDIX

This appendix presents a simplified version of the sketch generated by Chipmunk for a 2-by-2 grid (Figure 2) and a simple spec. We use... wherever appropriate to signify that the code is similar to code presented before. The full sketch is available here: https://gist.github.com/XiangyuG/1f009d812151f966b93c1fbf65bc0a69

// num_pipeline_stages = 2
// num_alus_per_stage = 2 (2 stateless ALUs + 2 stateful ALUs)
// num_phv_containers = 2

// Definitions of muxes and ALUs of the switch pipeline
// Input mux for each ALU
int stateless_alu_imux_0_0(int input0, int input1, int stateless_alu_0_0_imux1_ctrl_local) {
    if (stateless_alu_0_0_imux1_ctrl_local == 0) {
        return input0;
    } else {
        return input1;
    }
}
int stateless_alu_imux_0_1(int input0, int input1, int stateless_alu_0_1_imux1_ctrl_local) {...}
int stateless_alu_imux_1_0(int input0, int input1, int stateless_alu_1_0_imux1_ctrl_local) {...}
int stateless_alu_imux_1_1(int input0, int input1, int stateless_alu_1_1_imux1_ctrl_local) {...}

// Output mux for each PHV container
int omux_phv_0_0(int input0, int input1, int input2, int omux_phv_0_0_ctrl_local) {
    if (omux_phv_0_0_ctrl_local == 0) {
        return input0;
    } else if (omux_phv_0_0_ctrl_local == 1) {
        return input1;
    } else {
        return input2;
    }
}
int omux_phv_0_1(int input0, int input1, int input2, int omux_phv_0_1_ctrl_local) {...}
int omux_phv_1_0(int input0, int input1, int input2, int omux_phv_1_0_ctrl_local) {...}
int omux_phv_1_1(int input0, int input1, int input2, int omux_phv_1_1_ctrl_local) {...}

// Definition of ALUs
int stateless_alu_0_0_mux1(int input0, int input1, int stateless_alu_0_0_imux2_ctrl_local) {...}
int stateless_alu_0_0_mux2(int input0, int input1, int stateless_alu_0_0_imux2_ctrl_local) {...}
int stateless_alu_0_0(int input0, int input1, int opcode, int immediate, int imux1_ctrl_hole_local, int imux2_ctrl_hole_local) {
    int pkt_0 = stateless_alu_0_0_mux1(input0, input1, imux1_ctrl_hole_local);
    int pkt_1 = stateless_alu_0_0_mux2(input0, input1, imux2_ctrl_hole_local);
    if (opcode==0) {
        return pkt_0+pkt_1;
    } else if (opcode==1) {
        return pkt_0-pkt_1;
    } else if (opcode==2) {
        return pkt_0+immediate;
    } else {
        return pkt_0-immediate;
    }
}
int stateless_alu_0_1_mux1(int input0, int input1, int stateless_alu_0_1_imux2_ctrl_local) {...}
int stateless_alu_0_1_mux2(int input0, int input1, int stateless_alu_0_1_imux2_ctrl_local) {...}
int stateless_alu_0_1(int input0, int input1, int opcode, int immediate, int imux1_ctrl_hole_local, int imux2_ctrl_hole_local) {...}
int stateful_alu_0_0_Mode(int input0, int input1, int mode) {...}
int stateful_alu_0_0(ref int state_0, int pkt_0, int mode, int const_0) {...}
int stateful_alu_0_1_Mode(int input0, int input1, int mode) {...}
int stateful_alu_1_0_Mode(int input0, int input1, int mode) {...}
int stateful_alu_1_1_Mode(int input0, int input1, int mode) {...}
int stateful_alu_0_0(int input0, int input1, int mode) {...}
int stateful_alu_0_0(ref int state_0, int pkt_0, int mode, int const_0) {...}
int stateful_alu_0_1(int input0, int input1, int mode) {...}
int stateful_alu_1_0(int input0, int input1, int mode) {...}
int stateful_alu_1_1(int input0, int input1, int mode) {...}
// Data type for holding result from spec and implementation
struct StateAndPacket {
    int pkt_0;
    int state_0;
    int state_1;
}

// Specification
|StateAndPacket| program(|StateAndPacket| state_and_packet) {
    state_and_packet.pkt_0 = 1 + state_and_packet.state_0;
    state_and_packet.state_1 = state_and_packet.state_0;
    return state_and_packet;
}

// Implementation
|StateAndPacket| pipeline (|StateAndPacket| state_and_packet) {
    // Constraints to allocate state variables to stateful ALUs
    assert((salu_active_0_0 + salu_active_0_1 + 0) <= 2);
    assert((salu_active_1_0 + salu_active_1_1 + 0) <= 2);
    assert((salu_active_0_0 + salu_active_1_0 + 0) <= 1);
    assert((salu_active_0_1 + salu_active_1_1 + 0) <= 1);
    // Container i will be allocated to packet field i from the spec (canonical allocation).
    int input_0_0 = 0;
    int input_0_1 = 0;
    // One variable for each stateful ALU's state operand
    // This will be allocated to a state variable from the program using the salu_active indicator variables above.
    int state_operand_salu_0_0 = 0;
    int state_operand_salu_0_1 = 0;
    int state_operand_salu_1_0 = 0;
    int state_operand_salu_1_1 = 0;
    //*********** Stage 0 ***********/
    // Read each PHV container from corresponding packet field.
    int input_0_0 = state_and_packet.pkt_0;
    // Stateless ALUs
    int state_operand_salu_0_0 = stateless_alu_0_0(input_0_0,input_0_1,stateless_alu_0_0_opcode,stateless_alu_0_0_immediate,
        stateless_alu_0_0_imux1_ctrl,stateless_alu_0_0_imux2_ctrl);
    int state_operand_salu_0_1 = stateless_alu_1_0(...);
    // Stateful operands
    int packet_operand_salu0_0_0 = stateful_alu_imux_0_0(input_0_0,input_0_1,stateful_alu_0_0_imux_ctrl);
    int packet_operand_salu0_1_0 = stateful_alu_imux_0_1(...);
    // Read stateful ALU slots from allocated state vars.
    if (salu_active_0_0 == 1) {
        state_operand_salu_0_0 = state_and_packet.state_0;
    }
    if (salu_active_0_1 == 1) {...}
    // Stateful ALUs
    int state_alu_output_0_0 = stateful_alu_0_0(state_operand_salu_0_0,packet_operand_salu0_0_0,
        stateful_alu_0_0_mode_global,stateful_alu_0_0_const_0_global);
    int state_alu_output_0_1 = stateful_alu_1_0(...);
    // Outputs
    int output_0_0 = omux_phv_0_0(state_alu_output_0_0,state_alu_output_0_1,omux_phv_0_0_ctrl);
    int output_0_1 = omux_phv_0_1(state_alu_output_0_0,state_alu_output_0_1,omux_phv_0_1_ctrl);
    // Write stage
    if (salu_active_0_0 == 1) { state_and_packet.state_0 = state_operand_salu_0_0;}
    if (salu_active_0_1 == 1) { state_and_packet.state_1 = state_operand_salu_0_1;}
    //*********** Stage 1 ***********/
    // Input of this stage is the output of the previous one.
    int input_1_0 = output_0_0;
    int input_1_1 = output_0_1;
    // Write pkt_0 at the end of the pipeline.
    state_and_packet.pkt_0 = output_1_0;
    // Return updated packet fields and state vars
    return state_and_packet;
}

// Main sketch routine that asserts equivalence of pipeline and spec
harness void main(int pkt_0, int state_0, int state_1) {
    |StateAndPacket| x = |StateAndPacket|(pkt_0 = pkt_0, state_0 = state_0, state_1 = state_1);
    |StateAndPacket| pipeline_result = pipeline(x);
    assert(pipeline_result.state_0 == program_result.state_0);
    assert(pipeline_result.state_1 == program_result.state_1);
    assert(pipeline_result.pkt_0 == program_result.pkt_0);
}