High-level Synthesis: An Essential Ingredient for Designing Complex ASICs

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Abstract

It is common wisdom that synthesizing hardware from higher-level descriptions than Verilog will incur a performance penalty. The case study here shows that this need not be the case. If the higher-level language has suitable semantics, it is possible to synthesize hardware that is competitive with hand-written Verilog RTL. Differences in the hardware quality are dominated by architecture differences and, therefore, it is more important to explore multiple hardware architectures. This exploration is not practical without quality synthesis from higher-level languages.

INTRODUCTION

Five to ten million-gate ASICs are commonplace today. Their design typically takes 18 to 24 months and costs from $10M to $20M. An ASIC has a selling window of 6 to 8 months in the marketplace and, consequently, if the chip is delayed by much more than six months the customer is likely to leapfrog to the next generation chip, which is likely to be cheaper, faster, or have more features. Currently, in spite of a myriad of verification tools, three verification engineers are needed for each designer in typical ASIC teams. The verification task is exacerbated rather than abated by the use of pre-existing IP blocks. Only a small fraction of ASICs complete development in time to make money. Consequently, ASIC development has come to be viewed as an expensive and highly risky proposition.

Another casualty of the increasingly compressed development timeline is a thorough exploration of architectural alternatives. An alternative microarchitecture, perhaps inspired by a different algorithm, can often result in far greater time and area savings than any tweaking of a specific architecture. Consider adding a pipeline stage or functional unit, multiplexing an expensive resource, or doubling the datapath width while halving the clock rate. Determining the impact of these alternatives would require such a massive redesign as to be impractical using current methodologies. Although adding or removing datapaths and memories is relatively straightforward, the subsequent redesign and reverification of the control logic is not.

Commercial developments in CMOS technology make it likely that 50 million gate ASICs will be feasible by 2010. Such large ASICs will be commonplace only if EDA tools can keep up with the growing size and complexity of designs. What is needed is a high-level design methodology and accompanying tools that will allow complex digital systems to be realized by reasonably sized teams in a short time frame. The central themes of any such methodology have to be *correctness by construction*, *predictable functionality* and *predictable performance*. The methodology should make it as easy to use pre-existing IP blocks as it is to use procedural and data abstraction libraries in software, and should provide a framework that will simplify exploration of a large architectural design space by automatically generating correct control logic for any composition of instantiated library elements. To be successful, the quality of hardware synthesis from these high-level descriptions must approach that of hand-designed blocks so that designers are not tempted to break the abstractions.

This paper partially evaluates the Bluespec hardware design methodology that purports to have most of the characteristics described above. The methodology is based on synthesis from high-level hardware descriptions expressed as guarded atomic actions [11]. Bluespec [2] has been developed over the last four years, first at Sandburst Corporation and, now at Bluespec Inc.

Our method of evaluation is to take a small but nontrivial design problem and explore many different microarchitectures to implement it. We compare these microarchitectures in terms of area, clock cycle time, efficiency in solving the problem, robustness to changes in component characteristics and flexibility in dealing with changes in problem specification. We also compare the Bluespec generated results against hand-coded Verilog. The problem we have chosen is the much-studied "Longest Prefix Match" search engines which are present in all Internet routers. A solution must pass the same test suite on the same test bench to be acceptable.

Based on our study we conclude: 1. The differences in area and timing between different microarchitectural solutions are far greater than the differences in hand-written Verilog and Bluespec-generated Verilog. 2. If both Bluespec and Verilog are written by the same designer, the Bluespec compiler routinely generates code that is comparable to hand-written Verilog. 3. If the Verilog design is cleverly optimized, the Bluespec designer can usually imitate the Verilog designer to produce comparable results. 4. Architectural exploration is easier and quicker in Bluespec than in Verilog because the Bluespec methodology preserves correctness at every step and encourages the use of modules. 5. Though hard to quantify, Bluespec designs often take much less time to develop the first working model than comparable Verilog designs.

Paper organization.
The following section provides some background on guarded atomic actions as an HDL, and briefly explains automatic synthesis from them. The next three sections discuss the Longest Prefix Match problem, alternative design solutions, and how they are coded in Bluespec. After a section presenting experimental results for designs using this methodology, we discuss related work in high-level hardware design and our conclusions.

GUARDED ATOMIC ACTIONS AS HDL

Guarded atomic actions and modules

In the Bluespec methodology, the designer first explicitly instantiates the state elements of the system (registers, FIFOs, memories, etc.). That is, in Bluespec there is no mysterious or unpredictable "inferencing" of state from the program. Every bit of state (even a register) is a *module instance*, and clients of a module interact with it using *interface methods*. A call to an interface method looks like a procedure call, but every method also involves an *implicit condition*: a "ready" wire that specifies if the module can currently perform the requested method's action. For registers, the methods are the usual read() and write() operations, and the implicit conditions are always true (and will be optimized away). For FIFOs, the methods are the usual enq() and deq() operations. The implicit condition for enq() is true if the FIFO is not full; the implicit condition for deq() is true if the FIFO is not empty. A FIFO module may be visualized as shown in Figure 1.

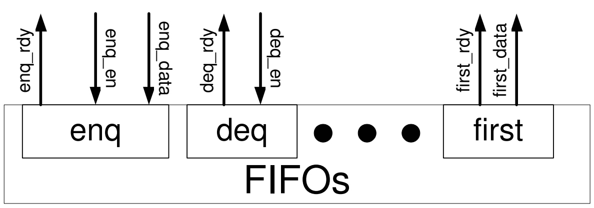

Figure 1. A FIFO Module.

Next, the designer describes the behavior of the system using a collection of *guarded atomic actions or rules*, which operate on the state of the system. Each rule specifies the condition under which it is enabled, and a consequent *allowable* (i.e., not compulsory) state transition. Two rules may access and update common state, but rules are written without regard to such interaction. In particular, rules have *atomic* semantics, i.e., the effect of each rule can be expressed and reasoned about in isolation, as if the rest of the system was frozen (see, for example, Arvind and Shen[1]). A precise and useful semantics emerges from the fact that any legitimate behavior of the system can be understood as a series of atomic actions on the state. Indeed, this is key to the high-level nature of rules: all the control circuitry and muxing needed to manage potential interactions between rules is produced by automatic synthesis as discussed in the next section.

Synthesis from guarded atomic actions

We briefly outline the synthesis approach of Hoe and Arvind [10, 11]. A rule consists of a guard and a body and may be written in the following form:

$$\text{Rule } R : \text{when } \pi(s) \; ==> \; s := \delta(s)$$

where π is the guard (predicate) and $s := \delta(s)$ is the body of rule R. Function δ is used to compute the next state of the system from the current state s. The execution model for a set of rules is to non-deterministically pick a rule whose predicate is true and then to atomically execute that rule's body. The execution continues as long as some predicate is true:

while (some π is true) do
1) select any $R,$ s.t. $\pi(s)$ is true
2) $s := \delta(s)$

There is a straightforward translation from rules into hardware as shown in Figure 2. Assuming all state is accessible (no port contention), each π and δ can be implemented easily as combinational logic. A hardware scheduler and control circuit then needs to be added so that in every cycle the scheduler dynamically picks one δ function whose corresponding π condition is satisfied and the control circuit updates the state of the system with the result of the selected δ function. The cycle time in such a synthesis is determined by the slowest π and the slowest δ functions. Although correct, such an implementation has unsatisfactory performance because it is often possible to execute several rules simultaneously such that the result of the execution matches an execution in which the selected rules are applied in some sequential order. Thus, the challenge in generating efficient hardware from sets of atomic actions is to generate a scheduler which in every cycle picks a maximal set of rules that can be executed simultaneously.

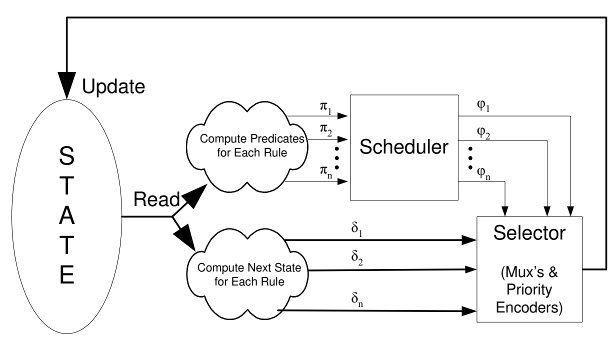

Figure 2. Synthesis from Guarded Atomic Actions.

It is easy to see that two rules can execute simultaneously if they are "conflict free", that is, they do not update the same state and neither updates the state accessed (i.e., "read") by the other rule. Arvind and Hoe further observed that two rules (R1 and R2) can execute simultaneously if one rule (R2) does not read any of the state that the other rule (R1) writes. In this case, simultaneous execution of R1 and R2 appears the same as sequential execution of R1 followed by R2. For this to hold, R2 writes must take precedence over writes to the same state by R1 and the execution of R1 must not disable R2. Such rules are called "sequentially composable" in [10, 11]. Hoe showed that from these pairwise relationships between rules one can deduce if a group of rules can be scheduled concurrently. Figure 2 shows the circuit that is generated in Hoe's synthesis flow. The predicates (π's) are computed for each rule using a combinational circuit. The scheduler is designed to select a maximal subset of applicable rules with the constraint that the outcome of a scheduling step can be explained as atomic firing of rules in some sequence. Based on which rules the scheduler chooses to enable (ϕ's), the selector block then combines the update functions (δ's) from the chosen rules and updates the current state with the resulting values.

An aggressive "mutual exclusion" analysis of rules is performed to eliminate scheduling cases that cannot arise logically. Without such an analysis one may unnecessarily commit resources, such as ports. One also needs a policy for selecting among the maximal schedules because different maximal sets can have different resource requirements. Construction of good schedulers is the most important problem in the synthesis of atomic actions. Recent work has made it possible to provide much better control over scheduling via modular composition and scheduling annotations (see, for example, Rosenband and Arvind[16], Nordin and Hoe[13] and Rosenband[15]).

A DESIGN PROBLEM: LONGEST PREFIX MATCH FUNCTION

The Longest Prefix Match (LPM) function is used in Internet Protocol (IP) packet routers to determine the output port to which an input packet should be forwarded based on the destination IP address (IPA) in the packet header. For IPv4 packets the IPA is 32 bits while for IPv6 it is 128 bits. We will consider solutions for IPv4 packets with an eye towards generalization to IPv6 packets.

LPM is based on a routing table which consists of a set of prefixes, each associated with an output port. Each prefix is a string of length ≤ 32 bits. High-end routers can contain more than 100K prefixes. Since more than one prefix can match an incoming IPA, the port associated with the longest matching prefix is selected as the output port.

The router must maintain packet order between the same source and destination. Packets must be processed at line rate (10 Gb/s today). This leaves a budget of typically < 10 memory references per packet. Memory size must be kept small for cost, board area, access rate and power reasons. A flat table would contain 2^{32} entries and is not feasible; sparse data structures are necessary. Finally, routes may change while the system is online.

Although many clever data structures have been devised for the LPM function, we use a simple tree data structure to illustrate our design approach. The lookup table is organized into three levels as shown in Figure 3. The first 16 bits of the IPA selects an entry from a root table containing 64K entries. If we find a leaf (output port number), we are done. Otherwise, we find a pointer to a 2nd-level table of 256 entries, which is indexed with the next 8 bits of the IPA. Again, we either find a leaf or a pointer to a 3rd-level table of 256 leaves indexed by the remaining 8 bits of the IPA. Each packet thus requires from 1 to 3 data dependent memory accesses. The data structure can be computed offline from any given routing table containing prefixes with lengths $\leq$ 32 bits.

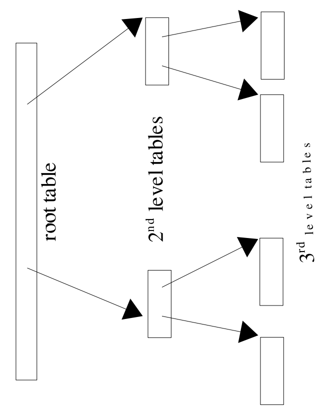

Figure 3. Data structure for Longest Prefix Match.

The following is a software implementation of LPM, written in a variant of C, extended with a Verilog-like bit extraction facility. Automatic generation of hardware from such a specification is close to impossible if the hardware is required to sustain 10 Gbps line rate.

```
int lpm(IPA  ipa)
{
    int p;
    p = RAM [rootTableBase + ipa[31:16]];
    if (isLeaf(p)) return p;
    p = RAM [p + ipa [15:8]];
    if (isLeaf(p)) return p;
    p = RAM [p + ipa [7:0]];
    return p; // must be a leaf
}
```

SOME ARCHITECTURAL ALTERNATIVES

We now describe three radically different architectural alternatives for a hardware implementation of LPM, and discuss their attributes, strengths and weaknesses. A key architectural restriction is that the entire data structure be kept in a single memory because of pin limitations and memory management flexibility. Assume that the memory is pipelined, and has a fixed latency of L cyles (> 1 cycle). Thus, in a pipelined implementation, the memory port is a shared resource across different stages of the pipeline, and at any given time the memory pipe will contain requests interleaved from different packets.

Statically scheduled pipeline.

The first design, whose schema is shown in Figure 4 and Figure 5, is a "rigid" pipeline architecture. For the first

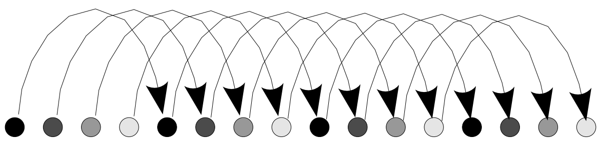

Figure 4. Statically scheduled memory references

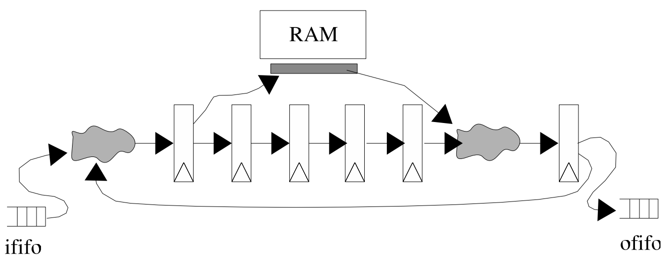

Figure 5. Rigid pipeline architecture

L cycles, we launch the first memory requests from each of the first L IPAs (assuming packets are available). Since each packet makes up to three memory accesses, no new packet is injected for the next $2L$ cycles. This guarantees that when the first memory response arrives, we can launch the second memory request for the first IPA (if it needs a second access), and so on. In summary, we completely statically schedule the pipeline, knowing the memory latency L and the maximum number of memory requests (three) for each IPA.

There are several issues with this design. The memory is fully utilized only if packets arrive at the highest rate (minimum-sized packets at line rate) and if they all need three memory references. Thus, the memory bandwidth is sized for the worst case, instead of the expected case. The latency and throughput in processing packets is fixed at the worst case (the length of the pipe) even if the actual workload contains packets requiring fewer memory references. The whole pipeline must be replanned if we are given a memory with a different latency. Finally, additional complex control is required to insert memory accesses for routing software to update the data structure online.

As we shall see in the Expermental Results section, even for statically scheduled pipelines there are several alternatives for organizing the state elements with very different implications for area and timing.

Flexible pipeline.

Figure 6 shows the second design, which has a "flexible" pipeline architecture. As each IPA arrives in `ififo`, `Stage0`

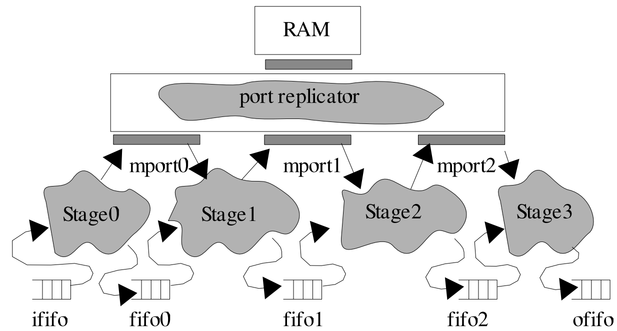

Figure 6. Flexible pipeline architecture.

launches its first memory request into `mport0` and keeps the IPA in `fifo0`. `Stage1` collects this IPA and the corresponding response from `mport0`. If done, it places the result and a "done" bit into `fifo1`, else it launches the second memory request into `mport1` and places the IPA and a "not done" bit into `fifo1`. `Stage2` and Stage3 act in a similar manner to Stage 1 with final results in `ofifo`. Notice, all FIFOs except `ififo` and `ofifo` must be of size L for full memory utilization.

The single memory is accessed through a "port replicator" module that takes requests as they arrive in any order on `mport0`, `mport1` and `mport2` and forwards them to the memory. Results from the memory are distributed back to these ports. Since the order of request arrivals is unpredictable, book-keeping circuitry (e.g., tagging) is required to return memory responses to the correct ports.

Although this design possibly requires more hardware and control logic (FIFOs, a port replicator with tagging, etc.), in many ways it is more robust than the previous design. For example, it would work correctly, though with reduced performance, if the memory latency is increased. It is relatively straightforward to extend it to a fourth port for updating the routing data structure online. Packets that require fewer memory accesses can traverse the pipeline faster, and so the design can exhibit a better latency and throughput than the worst case.

Circular pipeline.

Finally, Figure 7 shows a circular pipeline architecture, which is a folded version of the flexible pipeline. The `Input` stage takes an arriving IPA from `ififo` and a "ticket" from the Completion Buffer and launches a memory request using the high 16 bits of the IPA and places a (ticket,IPA[15:0],State$_0$) tuple into `cfifo`. Based on the memory response p and the first tuple (ticket,IPA,State$_j$) in `cfifo`, either the `Completion` or `Circulate` stage executes. If the lookup is done the `Completion` stage forwards (ticket,p) to the Completion Buffer else the `Circulate` stage places (ticket,IPA,State$_{j+1}$) into `cfifo` and launches another memory request based on

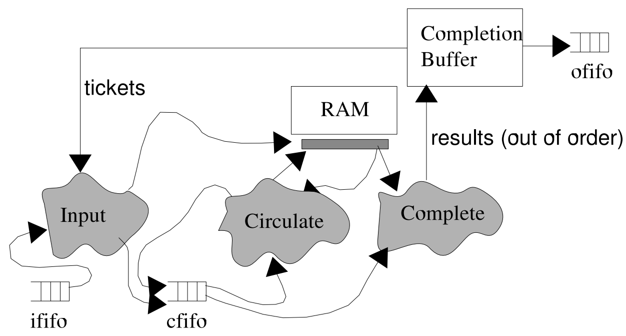

Figure 7. Circular pipeline architecture.

p and IPA.

Thus, each IPA goes around the pipe as many times as the number of needed memory references, and the result finally goes to the Completion Buffer. Since IPAs need varying numbers of memory references, results may arrive at the Completion Buffer out of order; the tickets allow it to output them into `ofifo` in the right order. In the worst case, for 100% memory utilization, the size of the Completion Buffer must be $2L$, though in practice a smaller buffer may suffice. To avoid deadlocks, the number of IPAs in the circular pipeline must not exceed the capacity of `cfifo` and a new IPA should have a lower priority to enter `cfifo` than an IPA already in the pipeline. The size `cfifo` must be L for 100% memory utilization.

This last design arguably has the simplest memory architecture (single port, no interleaving issues), but the most complex control (Completion Buffer with tickets and reordering). On the other hand it is very robust to different memory latencies and it generalizes easily to LPM on IPv6 (128-bit) addresses which require more memory references.

CODING IN BLUESPEC: CORRECTNESS BY CONSTRUCTION

We now give example fragments of Bluespec code for the three designs. These fragments have been edited due to space limitations, and use an earlier syntax for Bluespec (the current Bluespec product is based on SystemVerilog). These examples illustrate how designing with guarded atomic actions frees designers from worrying about global coordination allowing them to focus on the much simpler task of local correctness. The `Input` stage in the Circular Pipeline is expressed as follows:

```
Input:
  when (True) {
    ipa = ififo.pop;
    tkt = compBuf.getTicket;
    cfifo.enq({tkt, ipa[15:0], State0});
    RAM.readReq(base_addr + ipa[31:16]);
  }
```

Although the explicit condition in the rule is `True`, the rule is not enabled until all the implicit conditions are also true, i.e., until `ififo` contains an IP address, the completion buffer is willing to yield a ticket, and `cfifo` has room (is not full). In one succinct rule we have expressed a conceptual operation controlled by a complex set of conditions. The completion and recirculate rules are expressed as follows:

```
p = RAM.readResult;

Complete:
  when (isLeaf(p)) {
    {tkt,ipa,s} = cfifo.pop;
    compBuf.done({tkt, p});
    RAM.readAck;
  }

Circulate:
  when (!isLeaf(p)) {
    {tkt,ipa,s} = cfifo.pop;
    cfifo.enq({tkt, ipa, s+1});
    RAM.readReq(compute_addr(p,s,ipa));
    RAM.readAck;
  }
```

Both the `Input` and the `Circulate` rules enqueue into `cfifo`. To avoid deadlocks, the `Circulate` rule has to be given priority, or some other mechanism (such as an up-down counter) is needed to ensure that no more than L requests are enqueued into the circular pipeline. Given the priority between the rules, the Bluespec compiler automatically synthesizes the appropriate control logic. Similarly, control circuitry to manage the concurrent access to the shared completion buffer by the `Input` and `Complete` rules is automatically generated.

Atomicity of the actions in a rule plays a crucial role in avoiding races between enqueuing and dequeuing of `cfifo` and sending a request to the memory. The designer can reason about each rule in isolation to ensure that it is doing the right thing, without worrying about interactions with other rules. The synthesis method is guaranteed to preserve these atomic semantics while producing highly concurrent clocked synchronous hardware.

As another example, we consider the port replicator for shared access to a RAM from the Flexible Pipeline architecture of Figure 6. Figure 8 shows the organization of a 2-way port replicator. When a request arrives on `port0` and `port1`,

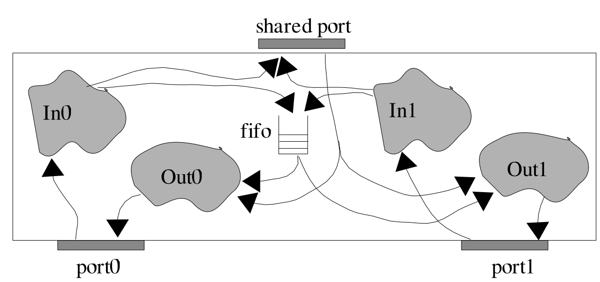

Figure 8. 2-way port replicator.

respectively, the In0 or In1 stages forward it to the shared port and place the tag "0" or tag "1" into the FIFO. When a response arrives from the shared port and "0" is at the head of the FIFO, the Out0 stage forwards the result to port0. If "1" is at the head of the FIFO, the Out1 stage forwards the result to port1. The behavior of In0 and Out0 are expressed as follows (In1 and Out1 have similar rules):

```
In0:
  when (True) {
    req0 = port0.pop;
    sharedPort.enq(req0);
    fifo.enq(Tag0);
  }
Out0:
  when (fifo.first == Tag0) {
    resp0 = sharedPort.pop;
    fifo.deq;
    port1.enq(resp0);
  }
```

Note that In0 and In1 can conflict: if requests arrive simultaneously on ports 0 and 1, both attempt to forward their requests into the shared port, and both attempt to enqueue a tag into the FIFO. Similarly, Out0 and Out1 both examine the shared port response and the head of the FIFO, and one of them dequeues from the FIFO. All the control circuitry for managing this interaction is synthesized automatically.

How does the designer assure himself that the identity of memory requests is accurately reflected in the tag FIFO, i.e., that In0 and In1 don't send requests to the memory in one order and enqueue their tags in the opposite order? Once again, atomicity comes to the rescue. It ensures that the order in the FIFO is exactly the same as the order of memory requests.

Now suppose we wish to generalize the port replicator to have the following features:

- N-way replication (not just 2 or 3)
- Requests of arbitrary type T1
- Responses of arbitrary type T2
- Parameterized by memory latency L

Bluespec solves this by allowing powerful composition of circuit elements which include Actions, Rules, Interfaces and Modules. Although not illustrated in this paper, Bluespec permits arbitrary programming with these objects and, thus, uses software expressivity primarily to describe circuit *structure*; behavior is specified entirely by Atomic Rules. In this approach, software expressivity does not face any ad hoc limits such as "synthesizable subsets." This is in sharp contrast with Behavioral Verilog and other C-based high-level synthesis approaches which use software expressivity to describe behavior.

EXPERIMENTAL RESULTS

All the Bluespec and Verilog codes for various designs were written by the authors. All designs were simulated using a shared testbench. The memory is fully pipelined with a latency of 4 cycles. Requests are inserted into the LPM design whenever possible, results are dequeued whenever possible. A simple compiler was used to translate prefix tables into appropriate data structures. The test data consisted of 9920 requests with an average of 1.908 memory references per request.

Bluespec designs were compiled using the Bluespec Compiler version 3.8.12, available from Bluespec Inc. The generated Verilog was compiled to the TSMC 0.18μm library using Synopsys Design Compiler version 2003.12. So as to achieve accurate timing and area results, the timing constraints were tuned to be within 500ps of the timing that the design could achieve. The worst case (slow process, low voltage) timing model was used. We divide area results by the area of a two input NAND2X1 gate (9.98μm^2) to obtain the reported gate counts.

Bluespec vs. hand-written Verilog synthesis comparison

The table in Figure 9 shows the best Bluespec and Verilog synthesis results for each of the three previously described longest prefix match architectures. The designs are nearly identical in both area and cycle times. The number of register bits varies slightly between the Verilog and Bluespec implementations because of small design choice differences and because the Bluespec compiler generates slightly different data and state machine encodings. The total gate count (combinational logic and registers) is within 8% in all designs, cycle time is within 7%, and as expected, simulation results between the Bluespec and Verilog designs match exactly.

The differences are within the noise margin of variations from repeated compilation with Synopsys Design Compiler with slightly different timing constraints. In general, the Bluespec results indicate slightly faster designs and slightly larger area (this is consistent with a study by Interra Systems of 25 small Bluespec and Verilog designs [4]). This can be explained through the generation of lower level code by the Bluespec compiler which in some cases makes the designs slightly faster and, because of different logic structuring, marginally larger. In comparison to the Verilog vs. Bluespec tradeoffs, area, cycle time and execution performance vary far more between designs with differing high-level and micro-level architectural choices.

Comparing the architectures we find that the smallest design, the static pipeline, is one seventh the size of the largest design, the flexible pipeline. Also, as expected, both the flexible and circular pipeline execute more efficiently than the static pipeline. In our test case 99.9% of the available memory bandwidth is utilized by the flexible and circular pipeline whereas the static architecture achieves only 63.5% memory utilization. These results are not entirely surprising, but we were impressed with how much smaller the circular pipeline is than the flexible pipeline. Our initial expectation was that they would be roughly equal in size. Because an optimized circulating loop and more efficient register alloca-

	Language	Timing cons-traint	Reg bits	Comb gates	% diff	Total gates	% diff	Cycle time (ns)	% diff	Through-put (cycles/ lookup)	Avg. latency (cycles)	Memory utili-zation
Static	BS	3.3ns	252	837	2%	2391	5%	3.32	-7%	3.001	17.0	63.5%
Static	Verilog	3.3ns	240	818		2271		3.56		3.001	17.0	63.5%
Flexible	BS	4.7ns	1219	6190	9%	15910	8%	4.7	0%	1.908	20.972	99.9%
Flexible	Verilog	4.7ns	1144	5685		14759		4.7		1.908	20.972	99.9%
Circular	BS	3.6ns	778	2391	3%	8170	1%	3.67	2%	1.908	14.814	99.9%
Circular	Verilog	3.6ns	778	2331		8103		3.62		1.908	14.814	99.9%

Figure 9. Results table 1

	Comments	Reg Bits	Comb Gates	% diff from best	Total Gates	% diff from best	Cycle Time (ns)	% diff from best
Static	BS; Initial; 3.3ns	252	1719	105%	3375	41%	3.69	11%
Static	BS; Data alignment; 3.3ns	252	1038	24%	2606	9%	3.48	5%
Static	BS; No type conversion; 3.3ns	252	948	13%	2478	4%	3.61	9%
Static	BS; Nest case (BEST); 3.3ns	252	837	0%	2391	0%	3.32	0%
Static	Verilog; Replicated; 3.3ns	243	7151	775%	8898	292%	3.60	1%
Static	Verilog; BEST; 3.3ns	240	818	0%	2271	0%	3.56	0%

Figure 10. Results table 2

tion could be used in the circular design, using the Bluespec language we were quickly able to determine that the circular pipeline is the superior design compared to the flexible pipeline. Through simulation the designer can then choose whether the static pipeline provides sufficient performance, or whether an area penalty should be incurred and the circular design be chosen.

Tweaking the Bluespec code

We also created two Verilog implementations of the static pipeline: one replicated much of the computation by unfolding the feedback of Fig. 5 into a linear pipe, the other (BEST) was highly optimized. Figure 10 shows that even in Verilog it is easy for two reasonable implementations to have dramatically different results. In this example the replicated implementation uses almost 9 times the combinational logic! The replicated design could easily have been the implementation of choice by a non-expert designer, and encourages the notion that microarchitecture is far more important than language results.

The initial Bluespec implementation of the static pipeline had over two times the combinational logic of the optimized Verilog implementation. Although better than the replicated design, a factor of two is usually an unacceptable penalty to pay knowingly for the use of a higher-level language. They illustrate that in some cases the abstractions that the language provides can introduce an overhead, but that this overhead can be overcome by carefully crafting the code. Our steps: 1) By carefully laying out data types several muxes and adders were removed. 2) By simplifying types we eliminated type-conversion logic. 3) A case statement was restructured to clarify that it was exhaustive. The circular pipeline took similar optimizations to achieve comparable performance to the Verilog implementation.

RELATED WORK

Designing using atomic actions

The approach advocated in this paper was first used for verification by Arvind and Shen [1]. Synthesis was later explored by Hoe and Arvind [10, 11]. Augustsson developed the Bluespec language [2] which introduced the notion of modules and a two-level language. In addition to internal work at Sandburst and Bluespec, this approach has been used by Hoe and Wunderlich at Carnegie Mellon, in cooperation with Intel. They have developed a version of the Itanium microachitecture running at 100 MHz on a 6M-gate FPGA. The FPGA board plugs into a processor socket in a dual-processor PC chassis and can exchange data with the other processor over the system bus at the rate of 800 MBytes/s. In another effort, Dave has used Bluespec in the design and synthesis of a reorder buffer [6].

Though the use of guarded atomic actions in verification has been much explored [5, 12, 7, 17, 3], there are only a few attempts at synthesis [14].

Modelling using C-based HDLs

There are several approaches to synthesis based on sequential and parallel C, e.g., [18, 8, 9], but they have rarely been competitive with hand-coded Verilog. There are myriad reasons for this. As one example, consider the difficulty of synthesizing control from parallel C. Suppose we code the circular pipeline of Figure 7 in some dialect of parallel C, i.e., C extended with processes together with some constructs for process synchronization such as semaphores, events and channels (e.g., SystemC). Each of the stages— input, circulation, and completion— becomes a separate sequential process. However, two major sources of complexity remain.

First, there is the issue of managing concurrent access to shared resources, such as the enqueues into `cfifo` by the `Input` and `Circulate` rules. When writing just for simulation, a simple lock will suffice. But when writing for synthesis, data paths must be properly multiplexed and controlled.

Second, there is the issue of complex control. Both the input and circulate/completion stages interact through `cfifo` and the Completion Buffer. The input stage is active only if `ififo` is not empty, `cfifo` is not full, and the Completion Buffer can issue a ticket. The circulate/completion stage is active only if a result from the RAM is available, if `cfifo` is not empty, and, depending on the RAM result, if either the Completion Buffer is ready to accept a result or if `cfifo` is not full. It is easy to make synchronization errors when using low-level primitives like semaphores, events and channels. Furthermore it is not clear if such complex synchronization code in C can be synthesized automatically. These synchronization issues are handled automatically in our approach based on guarded atomic actions.

In summary, while parallel C can be a fine medium to express behavior for simulation and perhaps for HW/SW co-verification, we believe it is not a good vehicle for expressing high-quality *synthesizable* hardware designs.

CONCLUSIONS

This study shows that high-level synthesis from guarded atomic actions as embodied in Bluespec provides a useful tool for microarchitectural exploration in the design of complex ASICs. The differences in area and time between different microarchitectures dominate differences between Bluespec-generated Verilog and hand-written Verilog.

Bluespec also provides a way of capturing the idioms commonly used in hardware design in a form that allows pervasive reuse. Existing hardware description languages only allow reuse at the level of fixed RTL modules with interfaces defined by sets of wires and cycle-level timing. Bluespec supports factoring of concepts such as buffered pipelines, completion buffers, and arbiters, into standard libraries. A designer can then instantiate these concepts with application-specific data types and connect them arbitrarily. The compiler will then synthesize an optimized design, including automatic generation of control logic. This approach raises the level of abstraction in hardware design without sacrificing hardware efficiency and may turn out to be the most crucial ingredient in designing large and complex ASICs in the future.

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