Elastic Silicon Interconnects
Abstracting Communication in Accelerator Design

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ABSTRACT
Communication is an important part of accelerator design, though it is under researched and under developed. Today, designers often face relatively low-level communication tools requiring them to design straightforward but error-prone plumbing. In this paper, we argue that raising the level of abstraction could yield correctness, productivity, and performance benefits not only for RTL-level designers but also for high level language developers.

1 INTRODUCTION
While there has been a huge amount of work in languages for hardware accelerator design, the communication networks to which they are connected has not seen much innovation lately. The euphemism ‘plumbing’ is often used, implying that the relatively mechanical task of moving data around to be a painful, necessary evil. Today, it is. RTL designers not only have to correctly implement a wire-level protocol, but correctly interpret the data blob which sits on the wires. High level languages generally expose some interfaces, but the data types on those ports are not known or enforced by tooling. High level languages do help to make typed communication with the host easy – as long as the designer works in the same vendors environment throughout the design on a board they support. In both cases, designers who do this “IP stitching” must often “gasket” interfaces and convert untyped data.

A high-level interconnect system should make these problems easier to solve. It should provide a common, high-level type system to enable inter-language communication and static type checking. It should automatically convert to/from various signaling standards (instead of defining a new one) and abstract away the details of wire-level signaling when the designer simply does not care. It should make host-accelerator communicate trivial regardless of the language, environment, or board the designer wants to use. It should enable incremental adoption of new technologies, easing integration of IP from an innovative tool. We could go on.

These problems motivated the Elastic Silicon Interconnects project (henceforth called ESI). At its core, ESI is an elastic interconnect compiler and a high-level type system. We then build on this to provide a rich set of features.

2 TYPES AND ELASTICITY
ESI uses connectivity specifications which are elastic[4] (based on latency-insensitivity[3]). This property provides the flexibility ESI needs to handle relatively mundane tasks like automatically pipelining connections, gearboxing (reducing or increasing the wire width of a connection), translating signaling standards, and crossing clock domains. Elasticity also allows ESI to route over other data transports, like PCIe to a host CPU or over an IP network to either a host or another accelerator.

Streaming channels in ESI transmit and receive typed messages. These types include the basic fixed size constructs: arbitrary width integers, enums, arrays, unions, and structs. We also support variable-length types – lists, namely. Lists get transmitted in chunks over multiple cycles. Both the transmitter and receiver will be allowed to select their own chunk sizes, which may be different – ESI will build the necessary gasket. Memory mapped regions will be modeled by structs which can be written to and read from.

Figure 1: An example ESI system with a performance monitor on the compressed data stream and an assertion on the encrypted data stream.

3 COMPOSABILITY
ESI’s elasticity and type information make systems easier to compose correctly. For software integration, we can construct typed software APIs for each connection. IP modules can be written in any language and be attached to other parts of the system (including the host) as long as the compiler speaks ESI or the designer specifies latency-insensitive connections and types. In both cases, static type safety can be enforced by the compiler.

These connections need not be to/from hardware either – ESI has co-simulation capabilities. One can use a generated API to talk to simulation then use the same API when graduating to hardware.
Alternatively, one could model an ESI systems IP modules with software emulators then replace them gradually as the hardware is developed. For longer IP module test runs, one could write the test bench in software then synthesize the module to run faster on an FPGA with the same API as in simulation.

4 FUTURES: MONITORING HOOKS
Accelerator design and use requires monitoring in various forms. During functional design, debugging is necessary and not fun. Staring at waveforms from a simulation and/or guessing where to insert probes in synthesized hardware is not productive. ESI can insert monitors on specified connections and capture/submit data only on valid messages vs every cycle. Since ESI knows the types, graphical debuggers could use that information to display debug information as intelligently and concisely as possible, either out of simulation or in hardware (with some trade-offs). One could also imagine inserting synthesizable assertions and being alerted on failure via a low-overhead aggregation network which ESI could automatically plumb out. When performance debugging, one could insert performance counters to get aggregate data on messages passing through ESI connections.

In production use, telemetry becomes necessary yet often added as an afterthought. It is often painful to plumb critical, low-bandwidth information out of the design. ESI can help in two ways: First, it could insert monitors of various types on its connections to monitor the interconnect activity in production. Second, it could construct low-bandwidth networks by serializing telemetry data into an arbitrarily low number of wires, saving resources. The ease and relatively low overheads involved in ESI telemetry should encourage more runtime telemetry earlier on to catch issues which occur during use at scale and with real workloads.

5 FUTURES: SERVICES AND BOARD SUPPORT
The future feature which enables bridging arbitrary ESI modules to host software and the monitoring hooks discussed above are ESI services. Any component instantiated by ESI can request a connection to a service, which will in turn provide some sort of specialized plumbing to said component. For instance, a ‘telemetry’ service could be provided to automatically wire up all the components which provide telemetry data. Users don’t usually care about the speed or way that telemetry is hooked up, so long as it works and is low overhead. Another example is an ‘assertion’ service, which components could use to alert a monitor that something has gone wrong, possibly with some location and debug data. RTL modules and high level language modules could also use services for common tasks, like low-bandwidth control-plane activities.

We can extend the notion of services to abstract away the board support packages (a.k.a. ‘shells’) into a set of standardized board support services. A ‘host communication’ service would provide components the ability to automatically connect to software, independent of the transport mechanism: PCIe, ethernet, or cosim. That service would be implemented hierarchically via a ‘PCle’ service, a ‘network’ service, etc. Board support services could even include ‘external memory’ services to connect to off-chip DRAM.

6 RELATED WORK
Networks on Chip. When designers think of interconnects, they tend to think of NoCs. Networks have become the standard for ASIC SoCs, and gain popularity in FPGAs[6, 8], though usually as a hardened component[2] or in the control plane. We, however, think of NoCs as a possible communication implementation. ESI could synthesize a NoC or something ad-hoc depending on the connections specified. If it or the designer chose a NoC, it could customize the topology and/or only provide partial connectivity. We believe that starting from a high level description of a designer’s requirements first then selecting an implementation has benefits.

System Designers. Tools like Qsys and Vivado IP Integrator make connectivity easier; however, they encourage vendor lock-in and remain low level. Being reductive for space reasons, they are essentially graphical NoC/SoC designers.

Integrated Development Environments. Commercial HLS environments often provide an automated build flow to synthesize a full software-to-hardware experience. They excel at integrating accelerators of a particular type and specific language. These tools, however, make anything that doesn’t fit in that mold difficult: integrating IP from multiple compilers, creating software APIs for unsupported languages, porting to different systems (et cetera) all become more difficult. ESI is just another tool – it produces code to a system spec and assumes that code compiles with the spec.

Services and host communication. Many of the concepts we discuss above were proposed and implemented in LEAP[5]. They implemented latency-insensitive channels which connect modules and use them to partition designs across FPGAs and provide services. ESI builds on LEAP (in an intellectual sense) in multiple dimensions. Sadly, LEAP never caught on, is relatively inaccessible as it is written in Bluespec, and has not seen any recent updates. Connectal[7] has an interface description language and it creates typed software-hardware RPC interfaces, similar to the off-chip features of ESI.

7 GOING FORWARD
All of the benefits of ESI apply equally to both hand-coded RTL and high level languages. A large part of our motivation is to enable both easier development of languages and adoption. In the ESI world, high level compilers are only responsible for spitting out ESI modules. Additionally, existing RTL designs need not trust the new compilers with their whole design as they can substitute their existing IP with the new one and compare. The intent is to enable easier on-boarding of higher level languages by ensuring they play nicely with each other, the existing RTL, and the system.

ESI is a nascent project intended for production use and is part of the CIRCT project. Today, it is capable of connecting ESI ports on modules (with configurable buffering) to each other or to cosimulation endpoints. Cosimulation communication is currently implemented via Cap’nProto RPC[1] so software drivers can be written in a multitude of languages. The current implementation does not yet support lists or gearboxes. Likewise, services need more development (both intellectual and engineering). We have lofty goals which won’t be achievable without community involvement.
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