Clippy(ing) Network Functions
Towards Better Abstractions for Checking & Designing Network Programs

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Abstract
When programming network functions, changes within a packet tend to have consequences—side effects which must be accounted for by network programmers or administrators via arbitrary logic and an innate understanding of dependencies. Examples of this include updating checksums when a packet’s contents has been modified or adjusting a payload length field of a IPv6 header if another header is added or updated within a packet. While static-typing captures interface specifications and how packet contents should behave, it does not enforce precise invariants around runtime dependencies like the examples above. Instead, during the design phase of network functions, programmers should be given an easier way to specify checks up front, all without having to account for and keep track of these consequences at each and every step during the development cycle. In keeping with this view, we present a unique approach for adding and generating both static checks and dynamic contracts for specifying and checking packet processing operations. We develop our technique within an existing framework called NetBricks and demonstrate how our approach simplifies and checks common dependent packet and header processing logic that other systems take for granted, all without adding much overhead during development.

1 Introduction
Writing network functions (NFs) today is as slick[4] and flexible as ever, as there are a plethora of frameworks and domain-specific languages to choose from. Some target development ease, reusable abstractions, or a familiar programming model that is in vogue within software development in the large, while others stress certain performance guarantees or better deployment at scale. This variety is a good thing. Nonetheless, no matter what framework or model is used, NFs tend to be comprised of code that exercises arbitrary logic and domain knowledge that only network programmers or administrators would know, or should know.

Consider the simple example of the payload length field of an IPv6 header, a field whose value is dependent upon the consequence of processing and manipulating the rest of the packet it’s a part of. For instance, if an extension header[7] is added or removed, or a layer 4 protocol’s payload is modified in any way, then this payload length field must be incremented or decremented accordingly. Other “middleboxes” downstream in the network will apply functionality based on the value held in this field—without calculating the length of the rest of the packet—or just drop the packet outright if it’s wrong. Handling this effect is often taken for granted, a piece of arbitrary logic that network programmers have to remember to apply and validate at different stages in a function pipeline or at egress. For example, in the still widely used[10, 20, 26] packet processing system Click[23], a CheckIPv6Header module, or element as its called, provides this snippet as a means to validate the payload length field:

```c
1 // check if the PayloadLength field is valid
2 if(ntohs(ip->ip6_plen) > (plen - 40))
3 goto bad;
```

While this code does do a “check” on the field, it hard codes the value of 40 into the if statement instead of using a constant or variable to better express meaning—40 is the fixed size of an IPv6 header. Additionally, if the check is invalid, goto bad executes a jump, leaving very little in the way of failure handling and unambiguous messaging. Besides a few other per-field validations within the element file, the module does not account for related changes downstream or the possible addition of extension headers; yet, it is supposed to be easily reused within chains of elements to compose larger, advanced Click programs. The functionality expressed in this snippet need not be so unwieldy, as validations should be a first-class component of any programmable network architecture.

In this paper, we present a novel approach that helps with clearly describing and validating these arbitrary effects via the addition and generation of both static checks and dynamic, runtime contracts for specifying conditional dependencies in common packet processing actions. Our work consists of three well-known programming paradigms:

- **Static Assertions and Types**

Our prototype is incorporated within a framework built using the Rust programming language, which emphasizes a strong, static type system with first-class polymorphism[34] (parametric and ad-hoc). Headers within a packet are explicitly-typed, e.g. MacHeader, IPv4Header, IPv6Header, for instance, and contain associated types[9] that define which header(s) can precede it, e.g. an IPv6 Header relies on an Ethernet header existing before it within a packet. We leverage the type system along with the concept of static assertions[21], to provide compile-time checking for a subset of network function components.

- **Design by Contract**

We take inspiration from D’s contract programming system[13], which in turn was inspired by design by contract schemes[27], where contracts are provided and run during testing, debugging, and development stages—the design phase—but are usually omitted for release builds in order to maximize performance. In using this style of contracts, programmers are able to code, test, and simulate NF’s around pre (ingress) and post (egress) invariants, checking which conditions must hold as packets are transformed by functions. These contracts allow developers to identify the intensional consequences of their packet processing algorithm(s).
• Code Generation

Though contract programming aids in identifying and checking if specifications and dependencies between operations hold, these checks are only (recommended to be) provided during time of development or within testing environments. Additionally, we do not want developers having to sprinkle contracts throughout their NFs or coding the logic in traversing or backtracking from one header, payload, or set of bytes to another just for the sake of validation. Instead, our approach takes on the unique concept of allowing developers to specify a set of dependencies and conditions up front via macros[22], which in turn get translated into contracts. Using this technique, programmers can work at a higher level of abstraction and not worry about optimizing or updating the body of their functions for every little change that takes place.

We develop our technique within an existing NF framework and programming model called Netbricks[31], showcasing our work through the lens of two NF cases: 1) updating the IPv6 payload length of a packet in the context of changes to an extension header; and 2) the transition of a invalid TCP packet, based on an MTU (Maximum Transmission Unit) threshold, into that of an ICMPv6 Packet Too Big response[6]. We also evaluate our prototype by examining syntax additions, compilation times, and possible runtime overheads (if used beyond the development/design stage). In Section 6, we discuss our cases within the context of a couple real-world examples, Onos and Facebook network code, where our approach could be beneficial.

2 Motivation
Choosing between NF architectures and/or network programming languages has become a non-trivial process, spurring more questions than answers: What type of programming paradigm should one choose for packet processing, i.e. functional, dataflow, imperative? Should the framework support the OpenFlow protocol or be composed of its own data plane and control plane layers? What are the most important facets of the system or application: performance, usability and reconfiguration, reliability? Is matching on prefixes and applying forwarding actions what’s most crucial? There are many choices to deliberate on and abstractions to choose from. The approaches run the gamut (6, 1), yet usually only provide a subset of safety, design benefits, or degrees of freedom for what types of applications can be executed. Here, we illustrate three specific challenges in defining a better way forward.

The Limits of Correctness In the scope of handling correctness and ensuring network programs satisfy specification, the research and experimentation is widespread. For example, a language like NetKat[3], based on proven semantic and type theoretic foundations, provides static checking for reachability, guarantees non-interference between programs, and supports first-class primitives for the filtering, modifying, and transmitting of packets. However, though powerful, NetKat is limited in what logic it can check for and what protocols and actions it can support, as all programs must conform to the OpenFlow flow table—its compilation target. While OpenFlow is definitely used in practice, its model is limited, and protocol and field support is dependent on release cadence. Where NetKat may fit the needs of certain network applications, it does not present a generalized solution that different frameworks can also implement.

| Decimal | Protocol                        | RFC | IANA |
|---------|---------------------------------|-----|------|
| 0       | Hop-by-Hop Options              | ✓   | ✓    |
| 43      | Routing                         | ✓   | ✓    |
| 44      | Fragment                        | ✓   | ✓    |
| 50      | Encapsulating Security Payload  | ✓   | ✓    |
| 51      | Authentication                  | ✓   | ✓    |
| 60      | Destination Options             | ✓   | ✓    |
| 135     | Mobility Header                 | ✓   | ✓    |
| 139     | Host Identity Protocol          | ✓   | ✓    |
| 140     | Shim6                           | ✓   | ✓    |
| 253     | Experiments/testing purposes    | ✓   | ✓    |
| 254     | Experiments/testing purposes    | ✓   | ✓    |

Figure 1: Extension Headers defined in RFC 2460 and IANA assignments; figure as per [17]

Arbitrary Logic and Variable-length Data As described in Section 1, many network programs contain operational logic that’s only applied based on the IETF or similar specifications they adhere to. Some even define their own inspired—by protocols without a formalized spec[19]. One major concept that has been left unsupported by many NF frameworks is that of IPv6 extension headers (Figure 1). Traffic containing such a header is usually dropped in practice and considered a “threat to the Internet”[17]. In skipping support for extension headers, packet-processing paradigms can avoid dealing with variable-length data—the specs of these headers contain fields with variable-byte-sized data—and complex header chaining dependencies—these headers can be stacked upon each other to no end. However, as unique applications for programmable networks are constantly being explored[8] that make use of these extensions, we must provide programmatic abstractions for adhering to the conditions of these protocols while also being amenable to new, experimental ones down the line whether they’re used in industry or proposed in research.

Members Only A major impetus for starting on this research was the fact that many “real-world” network applications and software “middleboxes” run on code that is weakly checked and difficult to extend (6). Network programmers and administrators typically understand their domain and limitations. Yet, in order to move further into making network programs and processes behave more “like software,” we must provide abstractions and designs for automated feedback for non-network developers to enter the space and apply new and exciting ideas on how to leverage the network for more interesting applications and forms of computation.

3 Kinds of Contracts
Before delving into our proposed implementation, we cover a bit more detail on what forms of checking and validation our approach combines, namely the trio of design by contract, static assertions, and statically ordered—persevering headers.
3.1 Design by Contract

In Section 1, we mention the inspiration we took from D’s contract programming system. Design by contract and the notion of assertions has its roots in formal verification, specification, and Hoare logic. The Eiffel programming language made design by contract first-class, focusing primarily on how these runtime contracts (assertions) can be turned on for monitoring and testing situations so that developers can “sit back, and just watch their contracts be violated”[28]. They key idea behind the approach is that elements of a software system collaborate with each other on the basis of mutual obligations and benefits—driven by dependencies and related components in the system. These contracts are usually separated into pre (input/ingress) and post conditions (output/egress), where invariants can be asserted on for incoming and outgoing data accordingly. For context, here is a simple example from a D-inspired Rust contract programming library[16]:

```rust
fn square_root(x: i64) -> i64 {
    assert!(x >= 0);
    \[ \text{result} = \sqrt{x}; \]
    \[ \text{assert!}((\text{result} \times \text{result}) \leq x \&\&(\text{result} + 1) \times (\text{result} + 1) > x); \]
    \[ \text{body} \]
    \[ (x \text{ as f64}).\sqrt() \text{ as i64} \]
}
```

In our system, design by contract-styled assertions help programmers articulate what the values of fields in a header should equal, not equal, be bound by, or be approximate to in relation to other fields in the packet or standardized values, upon execution during runtime. From the packet processing perspective, the input pre-condition runs when the packet enters a NF and the post-condition check runs as the packet is exiting the function.

3.2 Static Assertions

Static assertions, popularized in the C, C++, and D languages, allow for compile-time assertions of statically defined expressions, e.g. constants, statics. Beyond just checking for specific values, static assertions can be used to enforce fields on struct types and check if a pointer’s underlying value is the same when coerced to another type.

With our approach implemented within NetBricks, we were given a head start toward better validation mechanics with a strong, static type system and framework for programming NFs in a map-reduce-style fashion. To add packet headers in NetBricks, you define a struct with the appropriate fields, as you would do in C or P4 for example. All structs must implement a trait containing an associated type that is defined as PreviousHeader:

```rust
impl EndOffset for Ipv6Header {
    type PreviousHeader = MacHeader;
}
```

When parsing through a packet within an NF, the order is guaranteed by the defined PreviousHeader. Given any other order (e.g. parsing an IPv6 header after a ICMPv6 header), the type checker will throw a compile-time error. In our prototype, we leverage this statically-defined order mechanism on headers (4.1.1) to ensure that incoming and outgoing packet header ordering is preserved according to what the programmer expects it to be.

3.3 Static Order-Persevering Headers

4 Implementation

We have developed a prototype based on code generation (via macros) that extends the NetBricks programming model with very little additional syntax. Instead of having to manually incorporate or implement all the contract methodologies described in section 3 throughout a NF code base, our contracts extension can be used in a few easy steps:

- import our library into an NF module; then
- identify a network function you want to validate and mark it with the #[check] macro attribute; then
- specify pre and post-conditions at the beginning and end of a network function based on properties that the developer wants to uphold

Once included, these contract macros

- rewrite expressions;
- store runtime information for checking outgoing packet information on egress;
- generate assertions and logging facilities; and
- flag checks for conditional compilation—test/debug vs prod/release

4.1 Contract Generation

Figure 2 (a) illustrates the first few lines of an IPv6 Segment Routing Header-based NF example, which handles adding a segment to the packet’s segment stack[12]. On the right-hand side, (b), we demonstrate the diff once our code has been added for initialization, checking the order of the packet headers upon ingress (or input to the function). This example contains no pre-conditional dynamic contracts, but does perform the static assertion of a constant named BITS_128_TO_BYTES, which attempts to check and confirm that a 128-bit segment is indeed 16 bytes.
fn tcp_sr_nf<T: '_static + Batch<Header = Ipv6Header>>(parent: T) {
  parent.metadata(box \|\| pkt\|) {
    let v6h = pkt.get_header();
    let flow = v6h.flow().unwrap();
    MetadataT {
      Flow: FlowV6 {
        src_port: flow.src_port,
        dst_port: flow.dst_port,
        proto: flow.proto,
        ..Default::default()
      }...
    }
  }
}

Figure 2: Input section of NF; without (a) and with (b) checks/contracts

Initialization The check attribute macro (surrounded by brackets) is responsible for three steps in the generation process: 1) it annotates that the developer wants this NF to be "checked," as our prototype can be used on a per-NF level, gradually over time when necessary; 2) by designating that this function is one with contracts turned on, we are then able to spot for specific tokens and text, i.e. .pre, ingress_check! in the figure, that we want to rewrite; and 3) perform a series of initialization operations, including turning-on specialized logging facilities, lazily instantiating a runtime hashmap that's used to store all the headers as part of the input packet, copying the contents of incoming packet for storing and checking specifically, and producing a series of iterative steps to parse through the packet header-by-header, based on the order specified by the programmer.

Macro Expansion The generation of code from our macros occurs before the Rust type-checker takes hold of the NF program, meaning that type checking will occur on the generated code in a separate step of compilation. Just to demonstrate what macro expansion looks like, here's what the same code from Figure 2 (b) generally expands to structurally, after some cleanup for readability:

```rust
fn tcp_sr_nf<T: '_static + Batch<Header = Ipv6Header>>(parent: T) {
  parent.metadata(box \|\| pkt\|) {
    let v6h = pkt.get_header();
    let flow = v6h.flow().unwrap();
    MetadataT {
      Flow: FlowV6 {
        src_port: flow.src_port,
        dst_port: flow.dst_port,
        proto: flow.proto,
        ..Default::default()
      }...
    }
  }
}
```

Figure 3 shows how a pre-contract and post-contract are extended into an NF—one that checks if an incoming TCP packet is beyond the valid MTU threshold, and, if so, then rewrites the packet into an ICMPv6 Packet Too Big response; this response gets returned to the source sender. The incoming and outgoing order lists reveal how the packet should be transformed throughout the main body of the function. Egress checks compare the values of fields and functions on the current, outgoing packet, left-hand side of each check, to values that are either literal integers or integer expressions, or functions or fields from the original, incoming packet on the right-hand side. In this example, when the MTU threshold has been crossed, the outgoing ICMPv6 packet must return to sender, which means swapping both the Mac addresses and IPv6 source and destination addresses from the original input. The checks presented here would fail or throw errors in

```rust
let _pktIpV6Header = _pktMacHeader.parse_header::<Ipv6Header>();
...
.metadata(box ...
```

Highlighted in this code generation step is our assert on the constant, the copy and reset of the incoming packet, the accessing of our hashmap for storing header contents, and an explicitly-typed parse call on the IPv6 header pointer in the packet. By copying and resetting the packet to its origin pointer, we create a mirror of the contents of the packet entering the NF, to which we can store for tracing, analysis, and further checks throughout its processing lifecycle—all this preliminary setup work in the pre handler allows for more expressive post-condition checks at the egress part of the function.

The additional parse_header logic is determined by the programmer’s specified input order. All parsing of headers requires explicit type annotations in NetBricks, which allows us match the given order to the contents of the packet itself. If the expected order does not match up on either ingress or egress, a compile-time error is thrown (as per 3.3).

4.1.1 Ingress and Egress Contracts

Figure 3 shows how a pre-contract and post-contract are extended into an NF—one that checks if an incoming TCP packet is beyond the valid MTU threshold, and, if so, then rewrites the packet into an ICMPv6 Packet Too Big response; this response gets returned to the source sender. The incoming and outgoing order lists reveal how the packet should be transformed throughout the main body of the function. Egress checks compare the values of fields and functions on the current, outgoing packet, left-hand side of each check, to values that are either literal integers or integer expressions, or functions or fields from the original, incoming packet on the right-hand side. In this example, when the MTU threshold has been crossed, the outgoing ICMPv6 packet must return to sender, which means swapping both the Mac addresses and IPv6 source and destination addresses from the original input. The checks presented here would fail or throw errors in
As previously mentioned, design by contract-driven systems preach the idea of violating contracts during the simulation, testing, and debugging stages of program development. Our approach, however, combines these kinds of runtime, dynamic assertions, which capture arbitrary logic and values, with those like static assertions and compile-time type checking. Seen in our evaluation of the runtime and MTU validation); and, our log if the inner body’s logic did not account for these swap operations.

The high-level semantics for our macros flow as follows:

```

ingress_check! or egress_check!
{
  input: packet of bytes b,
  order: [τ₀ < τ₁ < τₙ],
  checks: [(current_pkt.$f : τ, $op, init_pkt.$f : τ ∨ $n)]
}
```

where $\text{op} \in \{<, >, \geq, =, \ldots\}$, $\text{f}$ is either a function or a field, and $\text{n}$ is a literal integer.

The ordering semantics preserve precedence based on the types provided and the checks can be indexed by the input (lhs) and output (rhs) header types they are a field or function of, unless they are just an integer value.

### 4.2 Conditional Compilation

As previously mentioned, design by contract-driven systems preach the idea of violating contracts during the simulation, testing, and debugging stages of program development. Our approach, however, combines these kinds of runtime, dynamic assertions, which capture arbitrary logic and values, with those like static assertions and compile-time type checking. Seen in our evaluation of the runtime costs of our prototype, 5.3, runtime-checking and initialization definitely accrue a penalty, which is manageable for non-release NF versions, but not for production ones. In order to keep static checks and assertions in the final releases of code and remove everything else that’s generated, our code generation step leverages Rust’s compile-time feature-flags[35] to only generate runtime contracts for debug or testing modes.

### 5 Evaluation

In this section, we evaluate the possible overheads of our approach for specification, specifically as it relates the development, or design-phase, of network functions. Additionally, we also profile what the runtime cost looks like by sampling the call graph during a packet’s run through an network function.

**Setup** In our experimental setup, we ran NetBricks within an Ubuntu Docker container on a local VirtualBox VM also running Ubuntu. NetBricks uses DPDK[31] for fast packet I/O, which we have properly set up within the VM and container. We used MoonGen[11] to generate varying packet captures (pcaps) for our testing and evaluation harness.

We looked at three figures of merit to evaluate our technique for the design of NFs while in test/debug mode:

* additional syntax (LoC - lines of code);
* compilation-time added to two of our example cases already discussed in the paper (appending to an extension-header and MTU validation); and,
* what the runtime overhead is via sample traces at the pre and post condition blocks.

### 5.1 Additional Syntax

Being that most of the work in our implementation is centered around the macro generation of contracts, it’s not surprising to see that in Table 1 our non-expanded measure of LoC is pretty minimal. We import a couple libraries, or crates as they are normally called in the Rust ecosystem, including our `check` library, into the NetBricks `main.rs` file. The additional crates are used for logging and assertion control around error handling and operations that we can match on. Minus some boilerplate, most of the additional code comes from the developer’s specifications themselves, as there is no bound on the number of possible validations, $n$ number of checks, they can add.

In Table 1, we choose to show LoC without expansion, as it’s from the perception of the developer of the NF. On the outset of this project, we wanted to avoid having to alter much of the core NetBricks internal code and APIs or the existing example network

| LoC run       | language | files | lines | code |
|---------------|----------|-------|-------|------|
| mtu-too-big: Contracts ON | rust | 2 | 214 | 183 |
| mtu-too-big: Contracts OFF | rust | 2 | 189 | 158 |
| mtu-too-big: Contracts ON | toml | 1 | 19 | 16  |
| mtu-too-big: Contracts OFF | toml | 1 | 16 | 13  |
| mtu-too-big: Contracts ON | total | 3 | 233 | 199 |
| mtu-too-big: Contracts OFF | total | 3 | 205 | 171 |

| Change | | +28 | +28 |

Table 1: Number of files, lines, and code for our MTU NF example’s code (macros not expanded)
functions. With our contract generation prototype, over multiple examples, we did not need to add more than 23 lines, less than ten percent, on the average to NF programs/modules and their build configuration files.

5.2 Compilation Times

In assessing our system and generation code, one of the most important factors we wanted to consider was compilation time, as we did not want programmers to pay much of a penalty while developing their NFs. Table 2 compares our two different network function cases with contract generation turned on and off. For each of these runs, the build was compiled from a warm, incremental cache and then consistently rebuilt from that cache a total of 10 times. In reading the table, with our contract generation system applied, the standard deviation across all builds was less than a second overall. In the case of our extension header example, the mean time was less than that of having no additional code applied at all. Though there is room for optimization in our macros, these results show that our technique doesn’t negatively affect a developer’s velocity during the design phase of development.

5.3 Runtime Cost

Throughout this paper, we’ve discussed how our target profile for programmers was to be able to specify their checks up front, including dynamic, logical checks across fields in headers of the packet as they build out NFs and test them. Knowing all of the initialization and setup we have to concoct on behalf of the contract engine, we knew that the runtime costs would be problematic if the NF ran in production. But, how problematic would it be?

For this evaluation, we spun up our invalid MTU example in debug mode, and ran a packet at a time through it, tracing the call graph throughout the function and sampling it. To trace and visualize the effect, we used the Flame Graph approach[15], popularized by Brendan Gregg and others writing infrastructure code for industry. The graph is illustrated in Figure 4, and, as expected, our pre-condition routine takes up a majority of the function’s execution time. This makes sense because this is the macro that generates a copy of the incoming packet and iteratively parses through every header within it. Our post/egress macro for example does much less and spans less of the execution graph.

With more performance optimization of our generation code, as well as some changes to how we store and parse the packet in the evaluated program, we should be able to lower the effect that our technique adds to the runtime. Nonetheless, as we’ve stated before, to focus our technique on the design phase of NF writing, the current version of the library compiles away most of this generated code upon production builds—not slowing down the runtime at all.

6 Discussion and Future Work

Thus far, we’ve demonstrated our technique on a few simple, yet practical NF examples. In this section, we discuss how our work could benefit practical programs and applications out in the wild. Then, we explore where we want to take the approach going forward.

6.1 Real-World Example: The ONOS Routing Class

One of the cases we’ve discussed already and demonstrated our technique on thus far is that of adding an additional (128-bit) segment to a IPv6 segment routing extension header. In Section 2, we mentioned that IPv6 extension headers were difficult to handle due to their variability, causing network operators to write rules to drop packets that contain them and NF frameworks avoiding their logic altogether. ONOS[5], the open network operating system, is a controller platform supporting a wide variety of SDN (Software-defined networking) use cases, including support for the Routing header extension. Nonetheless, the most complex logic that the header entails is that of adding and removing segments, which then triggers effects on the Last Entry (the index into the stack of segments) and Segments Left (the number of route segments remaining to be processed) fields. These triggered “events” provide a good story for our implementation because the ONOS class[1] does not account for changes in the Routing header stack; instead, it just works on a minimal set of fields for reading these headers along the network path. With an approach like the one we’ve exhibited in our paper, maybe more assurance can be given for handling the complex logic of variable-length information.

| compile times / cargo build | example          | mean (s) | stddev (s) | user (s) | system (s) | min (s) | max (s) |
|-----------------------------|------------------|----------|------------|----------|------------|---------|---------|
| Contracts - Off             | srv6-change-pkt  | 26.039   | 3.286      | 0.631    | 10.715     | 22.330  | 33.230  |
| Contracts - On              | srv6-change-pkt  | 25.099   | 2.398      | 0.549    | 11.697     | 20.238  | 28.220  |
| Effect                      |                  | -0.94    | -0.888     | -0.082   | +0.982     | -2.092  | -5.01   |
| Contracts - Off             | mtu-too-big      | 21.652   | 2.202      | 0.537    | 9.201      | 18.528  | 25.191  |
| Contracts - On              | mtu-too-big      | 26.052   | 1.858      | 0.650    | 10.851     | 22.165  | 28.346  |
| Effect                      |                  | +4.4     | -0.344     | +0.113   | +1.65      | +3.637  | +3.155  |

Table 2: Compile times running "cargo build" for extension header NF example and MTU NF example
We plan to continue developing our work for a future publication. Furthermore, what if constants like to explore two more novel opportunities that our approach can

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6.3.1 **Deployment Models**

Throughout this paper, we’ve explained how runtime assertions in our system are best used during the design phase of programming NFs. Yet, within the ecosystem of network programming, our technique can be extended beyond just design and integration testing. Moving forward, we’d like to be able to turn on contracts automatically if our system is running within an environment acting as a simulation network, e.g., Mininet[24], or within production deployments if it accepted only certain types of traffic, e.g., packets sent along for the sake of NF monitoring, health checking, and failure handling specifically.

6.3.2 **Hinting and Feedback**

The major goal of our work is aiding in the development and process of writing network programs, especially those that involve arbitrary complexity and interact with changing dependencies. Currently, in our system, runtime errors (being logged or not) look like this:

```
While we expect that a test suite would capture possible bugs in arbitrary logic and pointer references, there are no abstractions within the programs themselves to ensure the validity of fields and what values they can possibly be. Furthermore, what if constants like `MAX_PKT_SIZE` were changed within the upstream module that instantiated them? Would a test ensure that this particular send function has the correct value at the call site? Leveraging static assertions like we do in our work could benefit functions like the one shown here.

**6.3 Next Steps**

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```c
1 #attribute__(always_inline__)
2 static inline int send_icmp6_too_big(struct xdp_md *xdp) {
3 ...
4 struct ipv6hdr *ip6h, *orig_ip6h;
5 struct eth_hdr *orig_eth;
6 struct icmp6hdr *icmp6_hdr;
7 __u64 csum = 0;
8 __u64 off = 0;
9 orig_eth = data + headroom;
10 swap_mac(data, orig_eth);
11 off = sizeof(struct eth_hdr);
12 ip6h = data + off;
13 off = sizeof(struct ipv6hdr);
14 icmp6_hdr = data + off;
15 orig_ip6h = data + off;
16 ip6h->version = 6;
17 ip6h->protocol = IPPROTO_ICMPV6;
18 ip6h->hop_limit = DEFAULT_TTL;
19 ip6h->payload_len = htons(ICMP6_TOOBIG_PAYLOAD_SIZE);
20 memset(ip6h->flow_lbl, 0, ICMP6_PKT_TOOBIG);  //ollen
21 memmove(ip6h->flow_lbl, 0, sizeof(ip6h->flow_lbl));
22 memcpy(ip6h->daddr.s6_addr32, orig_ip6h->daddr.s6_addr32, 16);
23 memcpy(ip6h->saddr.s6_addr32, orig_ip6h->saddr.s6_addr32, 16);
24 icmp6_hdr->icmp6_type = ICMPV6_PKT_TOOBIG;
25 icmp6_hdr->icmp6_code = 0;
26 icmp6_hdr->icmp6_mtu = htonl(
27 sizeof(struct eth_hdr));
28 icmp6hr->icmp6_mtu = htons(0);
29 ipv6_checksum(icmp6_hdr, ICMP6_TOOBIG_PAYLOAD_SIZE, &csum, ip6h);
30 icmp6_hdr->icmp6_cksum = csum;
31 return XDP_TX;
32 }
```

Even though this error connotes some form of context—the expectation vs what actually happened—it does not articulate anything related to the specification itself or what dependencies triggered it. Going forward, we’d like to take a page from the recent work in program slicing and compiler design, i.e., Elm, Rust, and provide feedback and hints to the programmer while they build out NFs during development. Our plans for continuing this work include:

**Matching IETF specifications to program specifications**

In practice, when conforming to specification or applying new logic to a networking platform, many network engineers and administrators spend their time applying and manipulating code to match IETF, and similar, specs for certain protocols. How could we generate contracts based on these specs, instead of having the user apply the logic declaratively within pre and post-conditions? Our system could parse specifications as part of contract generation, given a protocol or header implementation, and generate a set of basic checks. We’d like to be able aid programmers by identifying useful specifications, especially as more complex applications are encountered.

**Leverage static analysis of input programs to find patterns and missteps**

In our code generation step(s) currently, we look for a set of explicit tokens to rewrite and incorporate seamlessly
within the context of a given network function. However, by adding the #check macro to a function, we’re able to walk the entire AST (Abstract Syntax Tree) of the input NF before it gets compiled, allowing us to perform static analysis on the function to find bugs[18] at compile-time. What would an heuristic-based NF bug-finding system look like, and how could that be helpful to programmers in this field? In leveraging analysis and strong static type-checking, we could limit the need for some runtime contracts, performing more compile-time checks—moving the code closer to production use cases.

**Interactive feedback** Good feedback is crucial when an error from a system or library bubbles up. Well-to-do type systems, for example, now provide more context to type errors (beyond just which line propagated the error itself), by suggesting types for the developer to substitute-in accordingly. In designing network function paradigms, we’d like to build off our prototype and expand to include helpful information about where contract errors occur, where more information can be found, and in what ways the errors can be fixed by the developer.

7 Related Work

Our approach extends a growing literature on contract-driven programming and systems for validating network function code. In Sections 1 and 3.1 we referenced how we were inspired by D’s contract programming model, which was itself inspired by the system developed for the Eiffel programming language. While our approach is unique within the field of programmable networks, contract programming has gained popularity as extensions to functional programming languages like Cloujure, via Spec[29], and Racket ‘contracts’[2]. The latter language also includes mechanisms for generating contracts from macros.

Regarding type systems, languages, and other means to validate and verify network programs, we’ve already mentioned NetKat[3] earlier in this work, and there have been many follow-up pieces regarding the language, including probabilistic variants[33]. Just recently, p4v[25] was published and is motivated by real-world examples; it attempts to find bugs in P4 programs and verify program properties by incorporating domain-specific assumptions into a constraint solver.

Languages for network function specification exist within industry, including TOSCA[30], a metamodel for templating for network function virtualization. Additionally, Assert-P4[14] is another proposed approach for checking P4 programs, and, like our work, is based on assertion checking. Combining assertions with symbolic execution, it find bugs motivated by controller misconfiguration and code circumvention and gives developers that ability to specify properties about their P4 programs. Their work is very P4-specific and does not provide examples of complex pipelines involving arbitrary dependencies, similar to the cases we’ve discussed—MTU and the Routing extension header.

8 Conclusion

In this paper, we provided an approach to and implementation for checking and validating the arbitrary logic and side effects typically part of network functions. Via user-driven specification and by leveraging and combining these three programming paradigms:

- design by contract (dynamic, runtime checks);
- static assertions and type-checking; and
- code generation via macros

we were able to build-out and incorporate our technique within an existing network function framework, all without penalizing the developer or increasing the complexity that they already have to handle. Going forward, we’d like to explore this space further and provide better tooling and interaction models for anyone wanting or needing to program networks.

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