Dynamic Recompilation of Software Network Services with Morpheus

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Abstract
State-of-the-art approaches to design, develop and optimize software packet-processing programs are based on static compilation: the compiler’s input is a description of the forwarding plane semantics and the output is a binary that can accommodate any control plane configuration or input traffic.

In this paper, we demonstrate that tracking control plane actions and packet-level traffic dynamics at run time opens up new opportunities for code specialization. We present Morpheus, a system working alongside static compilers that continuously optimizes the targeted networking code. We introduce a number of new techniques, from static code analysis to adaptive code instrumentation, and we implement a toolbox of domain specific optimizations that are not restricted to a specific data plane framework or programming language. We apply Morpheus to several eBPF and DPDK programs including Katran, Facebook’s production-grade load balancer. We compare Morpheus against state-of-the-art optimization frameworks and show that it can bring up to 2x throughput improvement, while halving the 99th percentile latency.

1 Introduction
Software Data Planes, packet processing programs implemented on commodity servers, are widely adopted in real deployments [9, 33, 40, 50, 68, 82, 88, 89]. This is because they do not require dedicated hardware, guarantee unlimited scale-out/scale-up, and are easier to debug than closed-source hardware [40]. Software data planes depend on a compiler toolchain (e.g., GCC [73] or LLVM [53]) to generate machine code, which can be potentially optimized offline through static transformations, e.g., inlining, loop unrolling, branch elimination, or vectorization [6,54]. Static optimizations, however, are independent of the actual input the code will process in operation, as this is unknown until then [11,24]. Consequently, the resulting generic code might contain logic for protocols and features that will never be triggered in a deployment, might be forced to perform costly memory loads to access values that are only known at run time, and take difficult-to-predict branches conditioned on variable data.

Dynamic compilation, in contrast, enables program optimization based on invariant data computed at run time and produces code that is specialized to the input the program is processing [7,24,34]. The idea is to continuously collect run-time data about program execution and then re-compile it to improve performance. This is a well-known practice adopted by generic programming languages (e.g., Java [24], JavaScript [34], and C/C++ [7]) and often produces orders of magnitude more efficient code in the context of, e.g., data-caching services [67], data mining [21] and databases [51,90].

To our surprise, we found that state-of-the-art dynamic optimization tools for generic software, including Google’s AutoFDO [21] and Facebook’s Bolt [67], are largely ineffective for network code (§2). We demonstrate that the performance of data plane programs critically depends on (i) network configuration, (ii) match-action table content and (iii) traffic patterns, and we argue that standard optimization tools [7,24,34] are ill-suited to exploit these domain-specific attributes (§2). Although several tools are available specifically for the networking domain (Table 2), most perform offline optimizations using recorded execution traces, requiring operators to tediously collect representative samples of match-action tables and predict traffic patterns from production deployments. To be practical, instead, a dynamic compiler for networking code should not depend on any offline profile, but rather work in a fully unsupervised mode where all tracing data needed for code specialization is collected online. In addition, existing tools are commonly tied to specific hardware, data plane framework, or programming language, limiting their applicability in specific scenarios.

We present Morpheus, a system to optimize network code at run time using domain-specific dynamic optimization techniques. Morpheus operates in a fully unsupervised mode, and it does not require any a priori knowledge about control plane configuration or data plane traffic patterns. We discuss the main design challenges (§3), such as automatically tracking highly variable input (e.g., inbound traffic) that may change
We introduce several novel techniques; we leverage static code analysis to build an understanding of the program offline and introduce a low-overhead adaptive instrumentation mechanism to minimize the amount of data collected online. Then, we invoke several dynamic optimization passes (e.g., dead code elimination, data-structure specialization, just-in-time compilation, and branch injection) to specialize the code against control plane actions and data plane traffic patterns. Finally, by injecting guards at specific points in the pipeline, we protect the consistency of the specialized code against changes to input that is considered invariant (§4).

Our implementation, Morpheus, exploits the LLVM JIT compiler toolchain to apply the above ideas at the LLVM Intermediate Representation (IR) level in a generic fashion and separates data plane specific code to several backend plugins to minimize the effort in porting Morpheus to a new architecture (§5). The code currently contains an eBPF and a DPDK/C plugin. We apply Morpheus to a number of packet processing programs, including the production-grade L4 load balancer Katran from Facebook (§6). Our results show that Morpheus can improve the performance of the unoptimized (statically compiled) eBPF application up to 94%, while reducing packet-processing latency by up to 123% at the 99th percentile. Applying Morpheus to a DPDK program, we increase performance by up to 469%. Finally, we measured Morpheus against state-of-the-art network code optimization frameworks such as ESwitch [62] and PacketMill [30]: we show that Morpheus boosts the throughput by up to 80% and 294%, respectively, compared to existing work.

**Contributions.** In this paper, we:

- demonstrate that tracking packet-level dynamics opens up new opportunities for network code specialization;
- design and implement Morpheus, a system working with standard compilers to optimize network code at run time;
- extensively evaluated Morpheus by applying it to two different I/O technologies (i.e., DPDK and eBPF), and a number of programs including production-grade software;
- share the code in open source to foster reproducibility (link-anonymized).

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### Table 1: A comparison of some popular dynamic optimization frameworks and Morpheus.

| Name             | Domain specific | Unsupervised adaptation to control plane actions | Unsupervised adaptation to data plane traffic | Data plane agnostic | Description |
|------------------|-----------------|-----------------------------------------------|---------------------------------------------|---------------------|-------------|
| Bolt [67]        | ✗               | -                                             | -                                           | ✓                   | Offline profile-guided optimizer for generic software code. |
| AutoFDO [21]     | ✓               | -                                             | -                                           | ✓                   | Offline profile-guided optimizer for DPDK-based software.  |
| eSwitch [62]     | ✓               | ✓                                             | -                                           | ✓                   | Policy-driven optimizer for DPDK-based OpenFlow software switches. |
| P5 [5]           | ✓               | ✓                                             | x                                           | x                   | Policy-driven optimizer for P4/RMT packet-processing pipelines. |
| P2GO [86]        | ✓               | x                                             | x                                           | x                   | Offline profile-guided optimizer for P4/RMT packet-processing pipelines. |
| PacketMill [30]  | ✓               | x                                             | x                                           | x                   | Policy-driven optimizer for network function virtualization. |
| NFReducer [69]   | ✓               | x                                             | x                                           | ✓                   | Run-time compiler and optimizer framework for arbitrary networking code. |
| Morpheus         | ✓               | x                                             | x                                           | ✓                   | Policy-driven optimizer for P4/RMT packet-processing pipelines. |

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### 2 The Need for Dynamic Optimization

To understand the performance implications of dynamic optimization on software data planes, we present a series of preliminary benchmarks using real network code. We consider two applications: the DPDK sample `firewall l3fwd-acl` [27], which performs basic L2/L3/L4 packet processing followed by a lookup into an access control list (ACL) containing a configurable number of wildcard 5-tuple rules, and Katran [40], Facebook’s open-source L4 eBPF/XDP load balancer. We connected two servers back-to-back by a 40GbE link, one server running the DPDK `Pktgen` traffic generator producing a stream of 64-byte packets at line rate [26], and the other running the application under test pinned to a single CPU core (see §6 for the details of the configuration).

**Generic tools fail to optimize network code.** In general, dynamic compilation opens up vast opportunities to improve performance. The question is, to what extent standard dynamic compilers can exploit these, when applied to network software? Fig. 1 presents the benchmark results for the DPDK firewall application at various levels of optimization using standard compiler tools. In particular, the baseline performance was measured with all optimizations disabled (level -00), consistently reaching 8.7 Mpps rate in our test. Enabling aggressive GCC static optimizations (level -03, [73]) yields 1.5× performance improvement (12.9 Mpps). This is not surprising; it is well-documented that typical C-level static program optimizations greatly benefit networking code [6, 54].

On top of static optimization, profile-guided optimization tools (PGO), like Google’s AutoFDO [21] or Facebook’s Bolt [67], promise to dynamically specialize the code for a specific input by recompiling it based on execution profiles recorded offline. However, our benchmarks indicate that for networking code this promise is not fulfilled; Bolt and AutoFDO could not bring sensible improvements (from 0.15% to 0.7%), even when the input traffic pattern matches the one used to train the optimization. Using AutoFDO and Bolt combined (see [67]), we obtained 1% performance increase.

We conclude that generic feedback-based dynamic optimization is mostly ineffective for networking code, as the offline execution profile does not give access to domain-specific metrics that are meaningful only in the packet processing context (e.g., match-action table access patterns and table sizes,
packet burst size, traffic profiles, or controller configuration).  

**Takeaway #1:** Generic dynamic optimization tools fail to optimize typical networking code. This calls for domain-specific dynamic optimizations, which take the specifics of the networking problem space into account.

**The promise of domain-specific dynamic optimization.**  
Most data-plane programs are developed as a single monolithic block containing various features that might be activated depending on the specific network configuration in use at any instance of time. For example, many large-scale cloud deployments still run on pure IPv4 and so the hypervisor switches would never have to process IPv6 packets [44] or adopt a single virtualization technology (VLAN/VxLAN/GRE/Genewe/GTP) and so switches would never see other encapsulations in operation [50, 66]. This implies that, depending on dynamic input that is unknown at compile time, a huge body of unused code gets assembled into the program, boosting code size and causing excess branch prediction misses, negatively impacting the overall performance [6, 55, 61, 69].

Removing unused code based on runtime configuration then can have a profound effect on software performance. To show this, we configured our DPDK firewall as a TCP signature-based Intrusion Detection System (IDS), with pure TCP wildcard rules generated with ClassBench [85]. This opens up a simple opportunity for optimization: all non-TCP packets can now directly bypass the ACL table, avoiding a wasteful lookup. Fig. 2 shows the runtime benefit of this optimization (under the **Runtime configuration** bar) for a synthetic input traffic trace where only about 10% of the input packets are UDP. Although around 90% of the traffic still has to undergo an ACL lookup, just avoiding this costly operation for a small percentage of traffic already increases performance with about 4.7%, without changing the semantic in any way.

In many practical scenarios, like DDoS blocking, security groups [10, 41] or whitelist-based access control, most firewall rules are fully-specified; for instance, in the official Stanford ruleset [48] on average ~45% of the rules are purely exact-matching. This opens up another dynamic optimization opportunity: add in front of the ACL an exact-matching lookup table to sidestep the costly wildcard lookup. The result in Fig. 2 (under the **Table specialization** bar) shows a further ~8% performance improvement with this simple modification.

A similar effect is visible with the load-balancer: configuring Katran as an HTTP load balancer [16, 64] allows to dynamically remove all the branches and code unrelated to IPv4/TCP processing, which reduces the number of instructions by ~58% (as reported by the Linux perf tool), yielding ~17.1% decrease in the number of L1 instruction cache-load misses. Better cache locality then translates into ~12% performance improvement (from 4.09 Mpps to 4.69 Mpps).

**Takeaway #2:** Specializing networking code for slowly changing input, like flow-rules, ACLs and control plane policies, substantially improves the performance of software data planes.

**The need for tracking packet-level dynamics.**  
The potential to optimize code for specific network configurations has been explored in prior work, for OpenFlow [62], P4 software [75, 86] and hardware targets [5], network functions [69], and programmable switches [30] (see Table 1). In order to maximize performance, however, we need to go beyond specializing the code for relatively stable runtime configuration and apply optimizations at the packet level.

Consider the DPDK firewall application. We installed 1000 wildcard rules and generated highly skewed traffic, so that from the thousand active unique 5-tuple flows only 5% accounts for 95% of the traffic. This opens up the opportunity to inline the match-action logic for the recurring rules. As the results show (Fig. 2, under the Fast Path bar), we obtain ~42% performance improvement with this simple traffic-dependent optimization. With the eBPF load balancer the effect is also visible: configuring 10 Virtual IPs (VIP) (both TCP and UDP), each with hundred different back-end servers, a similarly skewed input traffic trace presents the same opportunity to inline code, yielding ~24% performance edge.

**Takeaway #3:** For maximum performance, networking code must be specialized with respect to inbound traffic patterns, despite the potentially daunting packet-level dynamics.

### 3 Challenges

Static compilation performs optimizations that depend only on compile-time constants: it does not optimize variables whose value is invariant during the execution of the program but remain unknown until then. Dynamic compilation, in contrast, enables specializing the code with respect to invariant run time data [7]. This opens up a broad toolbox of optimiza-
tion opportunities, to propagate, fold and inline constants, remove branches and eliminate code never triggered in operation, or even to completely sidestep costly match-action table processing. The unsupervised optimization of networking code, however, presents a number of unique challenges:

**Challenge #1: Low-overhead run time instrumentation.** Unsupervised dynamic optimization rests on the assumption that program variables remaining invariant for an extended period of time are promptly detected. The prevalent approach is to collect instruction-level run-time profiles, record the input values and internal variables as well as the associated code execution paths. Then, use this profile to detect hotspots that may be tempting targets for dynamic optimization [7, 24, 35]. However, this is challenging at data-plane time scales: recording at run time instruction-level logs for code that processes potentially tens of millions of packets per second can introduce an overhead that makes the subsequent optimization pointless. We tackle this challenge in Morpheus by using static code analysis to understand the structure of the program offline (§4.1) and leveraging an adaptive instrumentation mechanism to minimize the amount of data that is collected online (§4.2).

**Challenge #2: Dynamic code generation.** Once run time profiling information is available, the dynamic compiler applies a set of domain-specific optimization passes to specialize the running code for the profile. Here, code generation must integrate seamlessly into the compiler toolchain, to avoid interference with the built-in optimization passes. Furthermore, a toolbox of domain-specific optimization passes must be identified, which, when applied to networking code, promise significant speedup (§4.2).

**Challenge #3: Consistency.** The dynamically optimized data plane is contingent on the assumption that the data considered invariant during the compilation indeed remains so: any update to such data would immediately invalidate the specialized code. Here, the challenge is to guarantee data plane consistency under any modification to the invariants on which the specialized code relies. We tackle this challenge by injecting guards at critical points in the code that allow the execution to fall back to the generic unoptimized path whenever an invariant changes. Since the performance burden on each packet, possibly taking several guards during its journey, can be taxing, we introduce a guard elision heuristic to sidestep useless guards (§4.3). To do so, our static code analysis tool must have enough understanding of the program to separate stateless from stateful code (§4.3). Finally, mechanisms are needed to atomically update the data plane once the code is re-optimized for the new invariants (§4.4).

**Challenge #4: Backend independence.** Software data planes may run on a diverse collection of backends, including kernel-based virtual machines [8, 38], kernel bypass frameworks [27], programmable software switches [14, 71] and network function virtualization engines [15, 37, 68]. In order to foster portability, the compiler should remain backend-agnostic as much as possible. We tackle this challenge by internally separating out the generic parts of the compiler toolchain into a backend-independent core and hiding backend-specific details behind a versatile backend API.

## 4 Morpheus Compilation Pipeline

We designed Morpheus with an ambitious goal: to build a portable dynamic software data plane compilation and optimization toolbox. The system architecture is shown in Fig. 3. Morpheus accepts the input code at the Intermediate Representation (IR) level. The pipeline is triggered periodically at given time slots to readjust the code for possibly changed traffic patterns and control plane updates. At each invocation, the compiler performs an extensive offline code analysis to understand the program control/data flow (see §4.1) and then reads a comprehensive set of instrumentation tables to extract run-time match-action table access patterns (see §4.2). Finally, Morpheus invokes a set of dynamic compilation passes to specialize the code (see §4.3) and then replaces the running data plane with the new, optimized code on the fly (see §4.4).

Below, we review the above steps in more detail. We use the simplified main loop of the Katran XDP/eBPF load balancer [40] as a running example (see Listing 1). The main loop is invoked by the Linux XDP datapath for each packet. It starts by parsing the L3 (line 4) and the L4 (line 5) header fields, using a special case for QUIC traffic as this is not trivial to identify [52]. In particular, QUIC flows are marked by a flag stored in the VIP record (line 12); if the flag is set, then a special function is called to deal with the QUIC protocol. Otherwise, a lookup in the connection table (line 17) is done: in case of a match, the ID of the backend assigned to the flow is returned; if no connection tracking information is found, a new backend is allocated and written back to the connection table (line 20). Finally, the IP address of the backend associated with the packet is read from the backend pool (line 24), the packet is encapsulated (line 25) and sent out (line 26).

### 4.1 Code Analysis

To be able to specialize code, we need to have a good understanding of the possible inputs it may receive during run time. Networking code tends to be fairly simplistic in this regard: commonly, the input consists of the context, which in eBPF/XDP corresponds to the raw packet buffers, and the content of match-action tables named maps in the eBPF world (Listing 1). Since input traffic may be highly variable and provides limited visibility into program operation, Morpheus does not monitor this input directly [6]. Rather, it relies on
tracking the map access patterns and uses this information to indirectly reconstruct aggregate traffic dynamics and identify invariants along frequently taken control flow branches.

In the first pass, Morpheus uses comprehensive statement-level static code analysis to identify all map access sites in the code, understand whether a particular access is a read or a write operation, and reason about the way the result is used later in the code. In particular, signature-based call site analysis is used to track map lookup and update calls, and then a combination of memory dependency analysis [4] and alias analysis [3] is performed to match map lookups to map updates. Maps that are never modified from within the data plane are marked as read-only (RO) and the rest as read-write (RW). Note that RO maps may still be modified from user space, but such control-plane actions tend to occur at a coarser timescale compared to RW maps, which may be updated with each packet. This observation will then allow to apply more aggressive optimizations to stateless code, which interacts only with relatively stable RO maps, and resort to conservative optimization strategies when specializing stateful code, which depend on potentially highly variable RW maps.

Running example. Consider the Katran main loop (Listing 1). Morpheus leverages the domain-specific knowledge, provided by the eBPF data-plane plugin (§5.1), to identify map reads by the map.lookup eBPF helper signature and map writes either via map.update calls or a direct pointer dereference. Thus, map backend_pool is marked as RO and conn_table as RW. For vip_map, memory dependency analysis finds an access via a pointer (line 12), but since this conditional statement does not modify the entry and no other alias is found, vip_map is marked as RO as well.

4.2 Instrumentation

In the second pass, Morpheus profiles the dynamics of the input traffic by generating heatmaps of the maps access patterns, so that the collected statistics can then be used to drive the subsequent optimization passes. Specifically, Morpheus uses a sketch to keep track of map accesses, by storing instrumentation data in a LRU (least-recently-used) cache alongside each map and adapting the sampling rate along several dimensions to control the run-time cost of profiling. The dimensions of adaptation are as follows. (1) Size: small maps are unconditionally inline of the code and hence instrumentation is disabled for these maps. (2) Dynamics: Morpheus does not record each map access, but rather it samples just enough information to reliably detect heavy hitters [29]. (3) Locality: instrumentation caches are per-CPU and hence track the local traffic conditions at each execution thread separately, i.e., specific to the RSS context. This improves per-core heavy hitter detection in presence of highly asymmetric traffic. (4) Scope: after identifying heavy hitters in the CPU context, local instrumentation caches are run together to identify global heavy hitters. (5) Context: if a map is accessed from multiple call sites then each one is instrumented separately, so that profiling information is specific to the calling context. (6) Application-specific insight: the operator can manually disable instrumentation for a map if it is clear from operational context that access patterns prohibit any traffic-dependent optimization (see Table 2). Traffic-independent optimizations are still applied by Morpheus in such cases.

Running example. Consider the vip_map in our sample program, identified as an RO map in the first pass. In addition, suppose that there are hundreds of VIPs associated with TCP services stored in the vip_map and only a single one is running QUIC, but the QUIC service receives the vast majority of run-time hits. Then, instrumentation will identify the QUIC VIP as a heavy hitter and Morpheus will seize the opportunity to specialize the subsequent QUIC call-path explicitly. Note that this comes without direct traffic monitoring, only using indirect traffic-specific instrumentation information.

4.3 Optimization Passes

The third step of the compilation pipeline is where all online code transformations are applied. Below, we describe the various run-time optimizations; see Table 2 for a summary.

4.3.1 Just-in-time compilation (JIT)

Empirical evidence (see §2) suggests that table lookup is a particularly taxing operation for software data planes. This is because certain match-action table types (e.g., LPM or wildcard), that are relatively simple in hardware, are notoriously expensive to implement in software [31]. Therefore, Morpheus specializes tables at run time with respect to their
Table 2: Dynamic optimizations in Morpheus. Applicability of each optimization depends on the map size, access profile (RO/RW), and availability of instrumentation information. Note that optimizations marked as “traffic-dependent” can also be applied, at least partially, without packet-level information (e.g., small RO maps can always just-in-time compiled). For full efficiency, these passes rely on timely instrumentation information (e.g., to JIT heavy hitters from a large map as a fast-path).

| Optimization                                | Description                                      | Small RO maps | Large RO maps | RW maps | Traffic-dependent |
|---------------------------------------------|--------------------------------------------------|---------------|---------------|---------|------------------|
| JIT (§4.3.1)                                | inline frequently hit table entries into the code|               |               | x       | x                |
| Table Elimination (§4.3.1)                  | remove empty tables                              |               |               | x       | x                |
| Constant Propagation (§4.3.2)               | substitute run-time constants into expressions   |               |               | x       | x                |
| Dead Code Elimination (§4.3.3)              | remove branches that are not being used          |               |               | x       | x                |
| Data Structure Specialization (§4.3.4)      | adapt map implementation to the entries stored   |               |               | x       | x                |
| Branch Injection (§4.3.5)                   | prevent table lookup for select inputs           |               |               | x       | x                |
| Guard Elision (§4.3.6)                      | eliminate useless guards                         |               |               | x       | x                |

content and dynamic access patterns, as learned in the instrumentation pass. Specifically, empty maps are completely removed, small maps are unconditionally just-in-time (JIT) compiled into equivalent code, and larger maps are preceded by a similar JIT compiled fast-path cache, which is in charge of handling the heavy hitters. Note that the consistency of the the fast-path cache must be carefully protected against potential changes made to the specialized map entries; Morpheus places guards into the code to ensure this (see later).

Running example. Consider again Listing 1 and suppose that there are only two VIPs configured in the vip_map. Being an exact-matching hash it is trivial to compile the vip_map into an “if-then-else” statement, representing each distinct map key as a separate branch. To do so, Morpheus uses the insights from the code analysis phase to discover that relevant fields in the lookup are the destination address (pkt.dstIP), port (pkt.dstPort) and the IP protocol (pkt.proto). Then, for each entry in the map, it builds a separate “if” conditional to compare the entry’s fields against the relevant packet header fields and chains these with “else” blocks. Since the instrumentation and the just-in-time compiled map are specific to unique combinations of destination address/port and protocol, the lookup semantics is correctly preserved even for longest prefix matching (LPM) caches and wildcard lookup.

4.3.2 Constant propagation

Specializing a table does not only benefit the performance of the lookup process: it also has far reaching consequences for the rest of the code. This is because a specialized table contains all the constants (keys and values) **inlined**, which makes it possible to propagate these constants to the surrounding code in order to inline memory accesses. In Morpheus, constant propagation opportunistically extends to larger maps that cannot be wholly just-in-time compiled: if a certain table field is found to be constant across all entries, then this constant is also inlined into the surrounding code. This optimization is thereby two-faceted: it can be used to specialize the code with respect to the inbound traffic (traffic-dependent, former case) but can also be applied without packet-level information (traffic-independent, the latter case). Morpheus does not implement constant propagation itself; rather, it relies on the underlying compiler toolchain to perform this pass.

Running example. Suppose there are only two backends in the backend_pool. Here, the map lookup (line 24) is rewritten into an “if-then-else” statement, with two branches for each backend. Correspondingly, in each branch the value of the backend variable is constant, which allows to save the costly memory dereference backend->ip (line 25) by inlining the backend IP address right into the specialized code.

4.3.3 Dead code elimination

Depending on the specific configuration, a large portion of code may sit unused in memory at any point in time. Such “dead code” can be found using a combination of static code analysis and the instrumentation information obtained from the previous pass. Upon detection, Morpheus removes all dead code on the optimized code path. As for the previous case, this operation is outsourced to the underlying compiler.

Running example. Consider the vip_map lookup site (line 10) and suppose that there are no QUIC services configured. As a consequence, the vip_info->flags is identical across all the entries in the vip_map and the constant propagation pass inlines this constant into the subsequent conditional (line 10). Thus, the condition vip_info->flags & F_QUIC_VIP always evaluates to false and the subsequent branch can be safely removed.

4.3.4 Data Structure Specialization

Morpheus adapts the layout, size and lookup algorithm of a table against its content at run time. For example, if all entries share the same prefix length in an LPM map, then a much faster exact-matching cache [62] can be used. This is done by first associating a backend-specific cost function with each applicable representation (this can be automatically inferred using static analysis and symbolic execution [67, 70]), generate then the expected cost of each candidate, and finally implement the table that minimizes the cost.

4.3.5 Branch Injection

This applies to the cases when certain fields take only few possible values in a table. In this situation, it is possible to
eliminate subsequent code that handles the rest of the values. Such an optimization was used in §2 to sidestep the ACL lookup for UDP packets in the firewall: if we observe that the “IP protocol” field can have only a single value in the ACL (e.g., TCP), then we can inject a conditional statement before the ACL lookup to check if the IP protocol field in a packet is TCP, use symbolic execution to track the use of this value throughout the resultant branch, and invoke dead code elimination to remove the useless ACL lookup on the non-TCP “else” branch.

### 4.3.6 Guard elimination

A critical requirement in dynamic compilation is to protect the consistency of the specialized code against changes to the invariants the optimizations depend on. Such changes can be made from the control plane or, when the program implements a stateful network function, even from the data-plane itself. A standard mechanism used by dynamic compilers to guarantee code consistency is to inject simple run-time version checks, called guards, at specific points in the code [39]. When the control flow reaches a guard, it atomically checks if the version of the guard is the same as the version of the optimized code; if yes, execution jumps to the optimized version, otherwise it falls back to the original code (“deoptimization”). Since each packet may need to pass multiple checks while traversing the datapath, guards may introduce nontrivial runtime overhead [87]. To mitigate this, Morpheus heuristically eliminates as many guards as possible; this is achieved by using different schemes to protect stateful and stateless code.

#### Handling control plane updates

Theoretically, each table should be protected by a guard when the contents are modified from the control plane. This would require packets to perform one costly guard check for each table. To reduce this overhead, Morpheus collapses all table-specific guards protecting against control plane updates into a single program-level guard, injected at the program entry point. Once an RO map gets updated by the control plane, the program-level guard direct all incoming packets to the original (unoptimized) datapath until the next compilation cycle kicks in to re-optimize the code with respect to the new table content.

#### Handling updates within the data plane

The optimized datapath must be protected from data-plane updates as well, which requires an explicit guard at all access sites for RW maps. If the guard tests valid then a query is made into the just-in-time compiled fast-path map cache and, on cache hit, the result is used in the subsequent code. Once a modification is made to the map from the program, the guard is invalidated and map lookup falls back to the original map.

Fig. 4 presents a breakdown of the strategies Morpheus uses to protect the consistency of optimized code. For RW maps (Fig. 4a), first an instrumentation cache is inlined at the access sites, followed by a guard that protects the just-in-time compiled fast-path against data-plane updates. Note that the constant propagation and dead code elimination passes are suppressed, since these passes may modify the code after the map lookup and the guard does not protect these optimizations. In contrast, RO map lookups (Fig. 4b and Fig. 4c) elide the guard, because only control-plane updates could invalidate the optimizations in this case but these are covered by the program-level guard. RO maps are specialized more aggressively than RW maps, by enabling all optimization passes. Finally, additional overhead can be shaved off for small RO tables by removing the fall-back map all together (Fig. 4c).

#### Running example

Once static code analysis confirms that the vip_map and backend_pool maps are RO, Morpheus opportunistically eliminates the corresponding guards at the call site. This then implies that, as long as the VIPs and the backend pool are invariant, the optimized code elides the guard. Since the conn_table map is RW, it is protected with a specific guard at the call site (line 17). Thus, the specialized map is used only as long as the connection tracking module’s state remains constant; once a new flow is introduced into conn_table (line 20) the specialized code is immediately invalidated by bumping the data-plane version. This does not invalidate all optimizations: as long as the rest of the (RO) maps are not updated by the control plane, the program-level guard remains valid and the corresponding RO map specializations still apply.
4.4 Update
Upon invocation, Morpheus executes the above passes to create the optimized datapath and uses the native compiler toolchain to transform the optimized code to target native code. Meanwhile, control plane updates are temporarily queued without being processed. This allows the “old” code to process packets without any disruption while the optimization takes place. Once compilation is finished, the optimized code is injected into the data path, the program-level guard is updated [36] and the outstanding table updates are executed.

5 Implementation
Morpheus is implemented in about 5940 lines of C++ code and it is openly available at link-anonymized. The code is separated into a data plane independent portable core, containing the compiler passes, and technology-specific plugins to interact with the underlying technology (i.e., eBPF, DPDK).

The Morpheus core extends the LLVM [53] compiler toolchain (v10.0.1) for code manipulation and run-time code generation. We opted to implement Morpheus at the intermediate representation (IR) level as it allows to reason about the running code using a relatively high-level language framework without compromising on code generation time. Moreover, this also makes the Morpheus core portable across different data plane frameworks and programming languages [80].

The data plane plugins are abstracted via a backend API. This API exports a set of functions for the core to identify match-action table access sites based on data-plane specific call signatures; compute cost functions for data structure specialization; rewrite data plane dependent code using templates; and provide an interface to inject guards. Additionally, the backend can channel instrumentation data from the data plane to the compiler core, implement the data plane dependency parts of the pipeline update mechanism, and provide a mechanism for the Morpheus core to inspect, and queue any update made by the control plane. The latter allows the compilation pipeline to be triggered when Morpheus intercepts a control plane event, e.g., an update to a table. Currently, only eBPF (fully) and DPDK (partially) are supported, but the architecture is generic enough to be extended to essentially any I/O framework, like netmap [76] or AF_XDP [2].

5.1 The eBPF Plugin
Morpheus leverages the Polycube [58] framework as an eBPF backend to manage chains of in-kernel packet processing programs. Polycube readily delivers almost all the needed components for an eBPF backend. We added a mechanism for updating the data plane program on-the-fly and defined templates to inject guards. We discuss these components next. Pipeline update. Once the optimized program is built, Morpheus calls the eBPF LLVM backend to generate the final eBPF native code, loads the new program into the kernel using the bpf() system call, and directs execution to the new code. In Polycube, a generic data plane program is usually realized as a chain of small eBPF programs connected via the eBPF tail-call mechanism, using a BPF_PROG_ARRAY map to get the address of the entry point of the next eBPF program to execute. Thus, injecting a new version of an eBPF program boils down to atomically update the BPF_PROG_ARRAY map entry pointing to it with the address of the new code. Guards. Morpheus relies on guards to protect the specialized code against map updates. The program-level guard is implemented as a simple run-time version check [36]. For stateful processing, Morpheus installs a guard at each map lookup site and injects a guard update pre-handler at the instruction address corresponding to the map update eBPF function (map_update_elem). This handler will then safely invalidate the guard before executing the map update.

5.2 The DPDK Plugin
Morpheus leverages FastClick [15], a framework to manage packet-processing applications based on DPDK. FastClick makes implementing most components of the backend API trivial; below we report only on pipeline updates and guards. Pipeline update. A FastClick program is assembled from primitive network functions, called elements, connected into a dataflow graph. Every FastClick element holds a pointer to the next element along the processing chain. To switch between different element implementations at run time, Morpheus adds a level of indirection to the FastClick pipeline: every time an element would pass execution to the next one, the corresponding function call is conveyed through a trampoline, which stores the real address of the next element to be called. Then, atomic pipeline update simplifies into rewriting the corresponding trampoline to the address of the new code. In contrast to eBPF, which explicitly externalizes into separate maps all program data intended to survive a single packet’s context, a FastClick element can hold non-trivial internal state, which would need to be tediously copied into the new element. As a workaround, our DPDK plugin disables dynamic optimizations for stateful FastClick elements. Guards. Since stateful FastClick elements are never optimized in Morpheus and RO elements maps always elide the guard, our DPDK plugin currently does not implement guards, except a program-level version check at the entry point.

6 Evaluation
Our testbed includes two servers connected back-to-back with a dual-port Intel X710 40Gbps NIC. The first, a 2x10-core Intel Xeon Silver 4210R CPU @2.40GHz with support for Intel’s Data Direct I/O (DDIO) [1] and 27.5 MB of L3 cache, runs the various applications under consideration. The second, a 2x10 Intel Xeon Silver 4114 CPU @2.20GHz with
13.75MB of L3 cache, is used as packet generator. Both servers are installed with Ubuntu 20.04.2, with the former running kernel 5.10.9 and the latter kernel 4.15.0-112. We also configured the NIC Receive-Side Scaling (RSS) to redirect all flows to a single receive queue, forcing the applications to be executed on a single CPU core, while Morpheus was pinned to another CPU core on the device-under-test (DUT).

In our tests, we used pktsgen with DPDK v20.11.0 to generate traffic and report the throughput results. Unless otherwise stated, we report the average single-core throughput across five different runs of each benchmark, measured at the minimum packet size (64-bytes). For latency tests, we used Moongen [28] to estimate the round-trip-time of a packet from the generator to the DUT and back. Finally, we used perf v5.10 to characterize the micro-architectural metrics of the DUT (e.g., cache misses, cycles, number of instructions).

In order to benchmark Morpheus on real applications, we chose four eBPF/XDP-based packet processing programs from the open-source eBPF/XDP reference network function virtualization framework Polycube [59], plus Facebook’s Katran load-balancer used earlier as a running example [40].

The L2 switch, the Router and the NAT applications were taken from Polycube [59]. The L2 switch use case is a functional Ethernet switch supporting 802.1Q VLAN and STP, with STP and flooding delegated to the control plane while learning and forwarding implemented entirely in eBPF, using an exact-matching MAC table supporting up to 4K entries. The Router use case implements a standard IP router, with RFC-1812 header checks, next-hop processing and checksum rewriting, configured with an LPM table of 2590 prefixes taken from the Stanford routing tables [49]. The NAT is an eBPF re-implementation of the corresponding Linux Netfilter application, configured with a single two-way SNAT/masquerading rule: the source IP of every packet is replaced with the IP of the outgoing NAT port and a separate L4 source port is allocated for each new flow. BPF−iptables is an eBPF/XDP clone [60] of the well-known Linux iptables framework, configured with 500 wildcard 5-tuple rules generated by Classbench [85]. Finally, Katran [40] was configured as a web-fronted, with 10 TCP services/VIPs and 100 back-end servers for each VIP.

For each benchmark, we generated 3 traffic traces with varying locality, to demonstrate the ability of Morpheus to track packet-level dynamics and optimize the programs accordingly. In particular, we created a high-locality traffic trace, where the top-5 flows account for 95% of the total traffic, a low-locality trace where the top-50 flows contribute 95% of the total traffic, and a no-locality trace with ~1000 different flows generated at random by a uniform distribution. Classbench comes with built-in trace generator, this was used for the BPF−iptables benchmarks. Each flow remains active for the entire duration of the experiments (see later on the dynamic benchmarks).

![Figure 5: Single core throughput (64B packets) varying input traffic locality. The optimizations adopted by Morpheus are traffic-dependent, while the ones from ESwitch [62] are not.](image)

![Figure 6: Effect of Morpheus optimizations on PMU counters, obtained with perf at the default frequency (40KHz). The top panel shows the percentage of decrease, per packet, of different metrics for high locality traffic (best-case for Morpheus), and the bottom panel for no locality traffic (worst-case).](image)

### 6.1 Benefits of Optimizations

First, we characterize the performance impact of Morpheus over the mentioned eBPF applications, when attached to the XDP hook of the ingress interface.

**Morpheus improves packet-processing throughput.** In Fig. 5, we show the impact of Morpheus under different traffic conditions. Throughout is defined as the maximum packet rate sustained by a program without experiencing packet loss. When a small subset of flows sends the majority of traffic (high-locality), Morpheus consistently provides more than 50% throughput improvement over the baseline, with a 2× speed-up for the Router. This is because Morpheus can track heavy flows and optimize the code accordingly. To confirm the benefit of packet-level optimizations in Morpheus, we compared it to a faithful eBPF/XDP re-implementation of ESwitch, a dynamic compiler that does not consider traffic dynamics [62]. The results (Fig 5) clearly show that Morpheus consistently delivers 5–10× the improvement compared to ESwitch for high-locality traces, while it essentially falls back to ESwitch for uniform traffic.

**Morpheus benefits at the micro-architectural scale.** Fig. 6 confirms that, by specializing code for the input the program is processing, it allows packet-processing programs to execute more efficiently. Morpheus reduces the last-level CPU
cache misses by up to 96% and effectively halves the instructions and branches executed per packet. At low or no traffic locality, the effects of packet-level optimizations diminish, but Morpheus can still bring considerable performance improvement; e.g., we see ~30% margin for BPF-iptables even for the non-locality trace. This is because the optimization passes in Morpheus are carefully selected to be applicable independently from packet-level dynamics (see Table 2).

**Morpheus reduces packet-processing latency.** We compared the 99th percentile baseline latency for each application against the one obtained with Morpheus, both in a best-case scenario when all packets travel through the optimized code path (e.g., the right branch in Fig. 4a), and a worst-case scenario with all packets falling back to the default branch instead of taking the fast-patch cache for each map (the left branch in Fig. 4a). The left panel in Fig. 7 shows the latency measured at low packet rate (10pps) so to avoid queuing effects [18], whereas the right panel shows latency under the maximum sustained load without packet drops [19]. First, we observe that Morpheus never increases latency, despite the considerable additional logic it injects dynamically into the code (guards, instrumentation; see below); in fact, it generally reduces it even in the worst case scenario. Notably, it reduces Katran’s packet-processing latency by about 123%.

### 6.2 What is the cost of code instrumentation?

Clearly, the price for performance improvements is the additional logic, most prominently, instrumentation, injected by Morpheus into the fast packet-processing path. To understand this price, we compared our adaptive instrumentation scheme (§4.2) against a naive approach where all map lookups are explicitly recorded. Fig. 8 shows that instrumentation involves visible overhead: the instrumented code performs worse than the baseline. The naive approach imposes a hefty 14–23% overhead, but adaptive instrumentation reduces this to just 0.9%–9%. Most importantly, this reduction does not come at a prohibitive cost: adaptive instrumentation provides enough insight to Morpheus to make up for the performance penalty imposed by it and still attain a considerable throughput improvement on top (see the green stacked barplots). In contrast, the performance tax of naive instrumentation may very well nullify optimization benefits, even despite full visibility into run-time dynamics (e.g., for the L2 switch or Katran).

We also studied the impact of packet sampling rate on instrumentation. Indeed, Morpheus collects information on packet-level dynamics only on a subset of input traffic in order to minimize the overhead. Fig. 9 highlights that Morpheus can strike a balance between overhead and efficiency by adapting the sampling rate. At a low sampling rate (e.g., recording every 100th packet) Morpheus does not have enough visibility into dynamics, which renders traffic-dependent optimizations less effective (but the traffic-invariant optimizations still apply). Higher sampling rates provide better visibility but also impose higher overhead. At the extreme (BPF-iptables, 100% instrumentation rate), optimization is just enough to offset the price of instrumentation. In conclusion, we found that setting the sampling rate at 5%–25% represents the best compromise.

### 6.3 How fast is the compilation?

In Table 3, we indicate with $t_1$ the time to analyze, instrument and optimize the LLVM IR code, and with $t_2$ the time it takes to generate the final eBPF code, starting from the LLVM IR. Note that $t_1$ is highly dependent on table size: the bigger the tables, the more time needed to read and analyze them. We show the results for high-locality traffic, which we consider the best case since Morpheus needs to track fewer flows, thus requiring lighter instrumentation tables that are faster to analyze, and a worst case when traffic with no-locality is fed
into the program. In general, table read time (i.e., t₁) dominates the compilation time, consistently staying below 100ms and reaching only for Katran in the worst-case scenario almost 600ms. This is because Katran uses huge static maps containing tens of thousands of entries to implement consistent hashing. Recent advances in the Linux kernel allow to read maps in batches, which would cut down this time by as much as 80% [81], reducing recompilation time for Katran below 100ms. Finally, the time needed to inject the optimized datapath into the kernel depends on the complexity of the program, since all eBPF code must pass the in-kernel verifier for a safety check before being activated. This also ensures that a mistaken Morpheus optimization pass will never break the data plane. In our tests, injection time varies between 0.5 to 3.4ms in the best case and at most 6.1ms in the worst case.

### 6.4 Morpheus in action

To test the ability of Morpheus to track highly dynamic inputs, we fed the **Router** application with time-varying traffic and observed the throughput over the time (Fig. 10). Recompilation period was conservatively set to 1 second. In the first 5 seconds we generate uniform traffic; here, the traffic-independent optimizations applied by Morpheus yield roughly 15% performance improvement over the baseline. At the 5th second, the traffic changes to a high-locality profile: after a quick learning period Morpheus specializes the code, essentially doubling the throughput. We see the same effect from the 0th second, when we switch to another high-locality trace with a new set of heavy-hitters, and also at 20 seconds, when we switch to a low-locality profile: after a brief training period Morpheus dynamically adapts the optimized datapath to the new profile and attains 60–100% performance improvement.

### 6.5 What can go wrong?

The flip side of dynamic optimization is the potential for a misguided run-time code transformation to harm performance. With generic languages this can happen when the dynamic compiler steals CPU cycles from the running code [24, 83]:

| Application | LOC | BPF Instruction | Compilation (ms) | Injection (ms) |
|-------------|-----|-----------------|-----------------|----------------|
|             |     |                 | Best | Worst | Best | Worst |
| L2 Switch   | 243 | 464             | 81   | 140   | 0.5  | 0.9   |
| Router      | 331 | 458             | 87   | 196   | 1.1  | 1.3   |
| BPF-iptables | 220 | 358             | 95   | 105   | 0.6  | 0.5   |
| Katran      | 494 | 905             | 287  | 1569  | 3.4  | 6.1   |

* Uses a chain of eBPF programs; since Morpheus optimizes every eBPF program separately, values shown refer to the most complex program in the chain.

^i Time to analyze the program, instrument it and read the maps.

^# Time to generate the final eBPF code.

in such cases careful manual compiler parameter tuning and deep application-specific knowledge is needed to make up for the lost performance [65]. Similar issues may arise with dynamically optimizing network code, as we show below on the **NAT** use case [59]. The NAT is organized as a single large connection tracking table, updated from within the data plane on each new flow. This represents a worst-case scenario for Morpheus: fully stateful code, so that guards cannot be opportunistically elided, coupled with potentially very high traffic dynamics beyond our control. Yet, since traffic-independent optimizations can still be applied (Table 2) Morpheus can improve throughput by around 5% (from 4.36 to 4.58 Mpps) in the presence of high-locality traffic. However, for low-locality traffic we see about 6% performance degradation compared to the baseline. Intuitively, Morpheus just keeps on recompiling the conntrack fast-path with another set of potential heavy hitters, just to immediately remove this optimization as a new flow arrives. Our tests again mark micro-architectural reasons behind this: the number of branch misses and instruction cache loads increases by 90% and 75%, respectively, both clear symptoms of frequent code changes. The rest of the stateful applications (**L2 switch** and **Katran**) exhibit a similar pattern, but the speed-up enabled by dead code elimination, constant propagation and branch-injection can make up for this. As with Java, such cases require human intervention; manually disabling optimization for the connection tracking module’s table safely eliminates the performance degradation on the **NAT** use case.

### 6.6 Morpheus with DPDK programs

We also applied Morpheus to a DPDK program, namely the **FastClick** [15] version of the eBPF **Router** application. We configured the router with either 20 or 500 rules taken from the Stanford routing tables [49] and generated traffic with different levels of locality as before. We tested the throughput and the latency of the baseline code and the Morpheus optimized one and we compared the results to a state-of-the-art DPDK packet-processing optimizer, PacketMill [30]. In our tests PacketMill uses the following optimizations: removing virtual function calls, inlining variables, and allocating/defining the elements’ objects in the source code.

Fig. 11 reports the average throughput results. For only 20
7 Related work

Generic code optimization has a long-standing stream of research and prototypes [13, 21, 42, 45, 63, 67, 72, 77]. In the context of networking, domain-specific data-plane optimization has also gained substantial interest lately.

Static optimization of data-plane programs. Several packet I/O frameworks present specific APIs for developers to optimize network code [22, 23, 32, 37, 68], or implement different paradigms to efficiently execute packet-processing programs sequentially or in parallel [12, 46, 55, 57, 78, 84]. Other proposals aim to remove redundant logic or merge different elements together [20, 47, 79]. These works, however, provide predominantly static optimizations; Morpheus, on top of these static optimizations, also considers run-time insight to specialize generic network code.

Dynamic optimization of packet-processing programs. ESwitch [62, 75] was the first functional framework for the unsupervised dynamic optimization of software data planes with respect to the packet-processing program, specified in OpenFlow, being executed. PacketMill [30] and NFReducer [25] leverage the LLVM toolchain [53] instead of OpenFlow: PacketMill targets the FastClick datapath by exploiting the DPDK packet I/O framework and NFReducer aims to eliminate redundant logic from generic packet-processing programs using symbolic execution. Morpheus is strictly complementary to these works: (1) it applies some of the same optimizations but it also introduces a toolbox of new ones (e.g., branch injection or constant propagation for stable table entries); (2) Morpheus can detect packet-level dynamics and apply more aggressive optimizations depending on the specific traffic patterns; and (3) Morpheus is data-plane agnostic, in that it performs the optimizations at the IR-level using a portable compiler core and relies on the built-in compiler toolchain to generate machine code and a data-plane plugin to inject it into the datapath.

Profile-guided optimization for packet-processing hardware. P2GO [86] and P5 [5] apply several profile-driven optimizations to improve the resource utilization of programmable P4 hardware targets. Some of the ideas presented in this work can also be used with programmable P4 hardware, provided it is possible to re-synthesize the packet processing pipeline without traffic disruption, with a notable difference: P2GO and P5 require a priori knowledge (i.e., the profiles) while Morpheus aims at unsupervised dynamic optimization.

8 Conclusion

We presented Morpheus, a run-time compiler and optimizer framework for arbitrary networking code. We demonstrated the importance of tracking packet-level dynamics and how they open up opportunities for a number of domain-specific optimizations. We proposed a solution, Morpheus, capable of applying them without any a priori information on the running program and implemented on top of the LLVM JIT compiler toolchain at the IR level. This allows to decouple our system from the specific framework used by the underlying data plane as much as possible. Finally, we demonstrated the effectiveness of Morpheus on a number of programs written in eBPF and DPDK and released the code in open-source to foster reproducibility of our results.

We consider Morpheus only as a first step towards more intelligent systems that can adapt to network conditions. As future work, we intend to integrate a run-time performance prediction model [17, 43, 56, 70, 74] into Morpheus, which enables the compiler to reason about the effect of each different dynamic optimization pass. This would allow for selecting the most efficient subset of optimizations and adapt the re-compilation timescales to the current network conditions.
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