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everparse3D

Hardening Attack Surfaces with Formally Proven Message Parsers

Nikhil Swamy Tahina Ramananandro Aseem Rastogi
Irina Spiridonova Haobin Ni Dmitry Malloy
Juan Vazquez Michael Tang Omar Cardona Arti Gupta

Microsoft

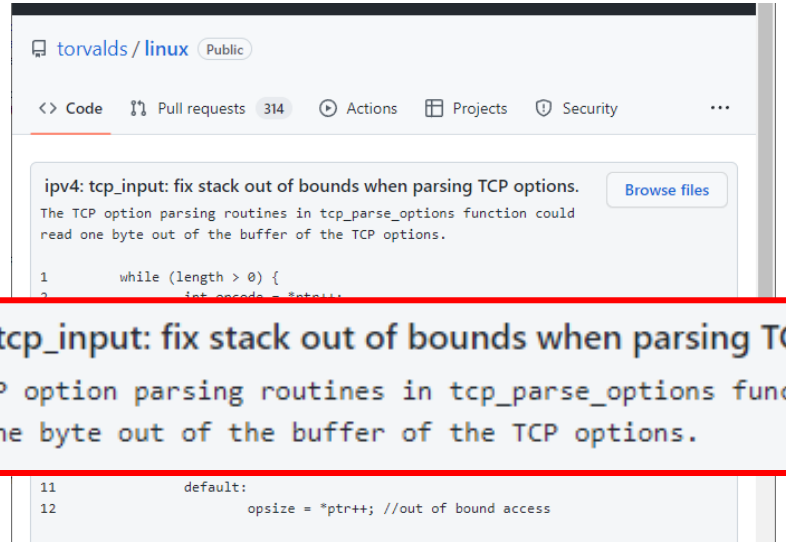
RiSE

everest
Verified End-to-End Secure Transport

Secure Parsing is Critical

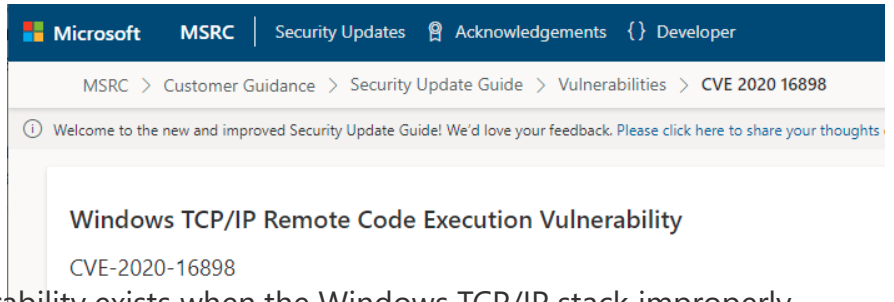
- Improper input validation = MITRE 2020 Top #3, 2021 Top #4 most dangerous CVE software weakness

- Still a thing today in widely-used >30-year-old formats
  - Linux TCP parsing bug fix as late as 2019
  - Windows 10 Bad Neighbor (ICMPv6, 2020)



ipv4: tcp_input: fix stack out of bounds when parsing TCP options.

The TCP option parsing routines in tcp_parse_options function could read one byte out of the buffer of the TCP options.



A remote code execution vulnerability exists when the Windows TCP/IP stack improperly handles ICMPv6 Router Advertisement packets. An attacker who successfully exploited this vulnerability could gain the ability to execute code on the target server or client.

To exploit this vulnerability, an attacker would have to send specially crafted ICMPv6 Router Advertisement packets to a remote Windows computer.

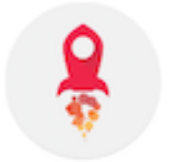
The update addresses the vulnerability by correcting how the Windows TCP/IP stack handles ICMPv6 Router Advertisement packets.

Handwritten parsing still around

- Handwritten C/C++ code
  - Performance, deployability (e.g. OS kernel), legacy

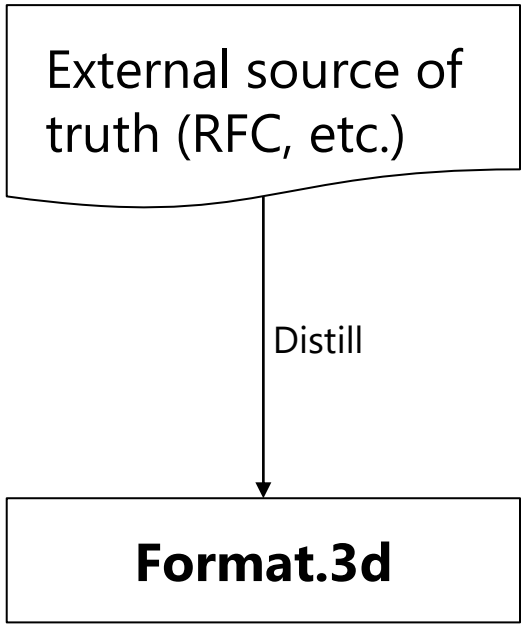
- Bratus et al. (Usenix Mag. 2017), LangSec:
  - “Roll your own crypto” considered harmful
  - “Roll your own parsers” also should be

- Ongoing push for automatically generated parsers
  - ProtocolBuffers, FlatBuffers, Cap’n Proto, JSON…
  - But those libraries choose the data formats
  - **What about formats dictated by external constraints?** (TCP, ICMP…)



Our Solution: EverParse3D

1. Author spec



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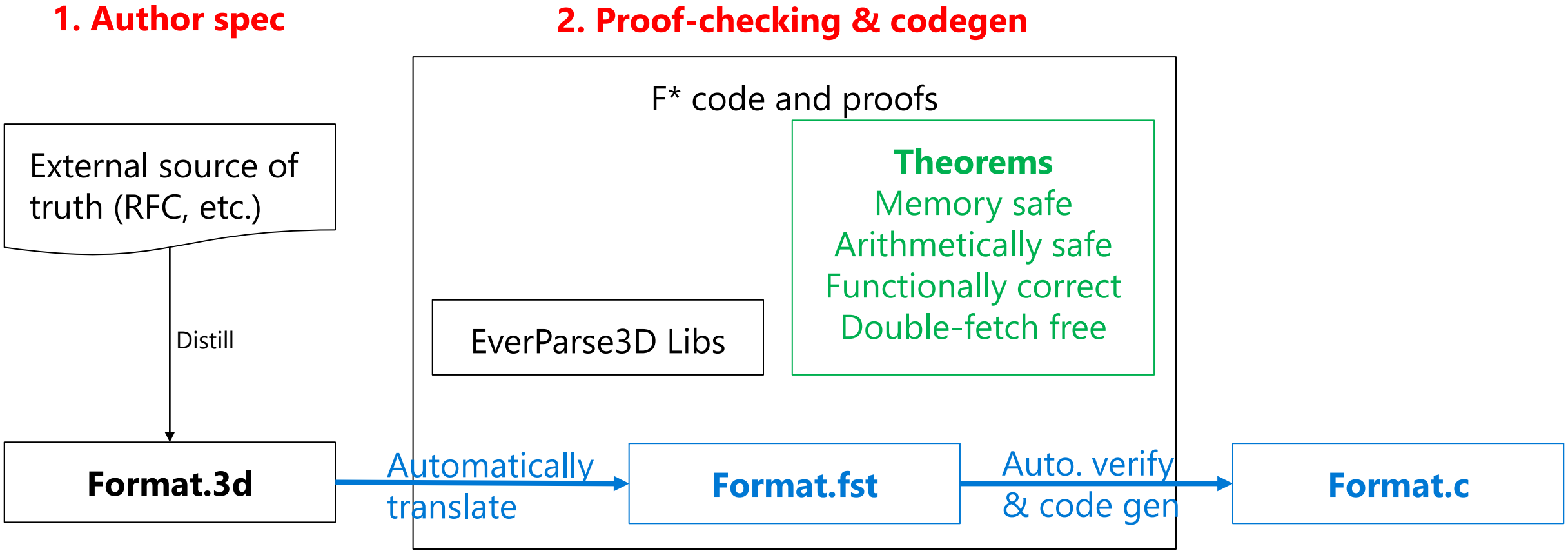

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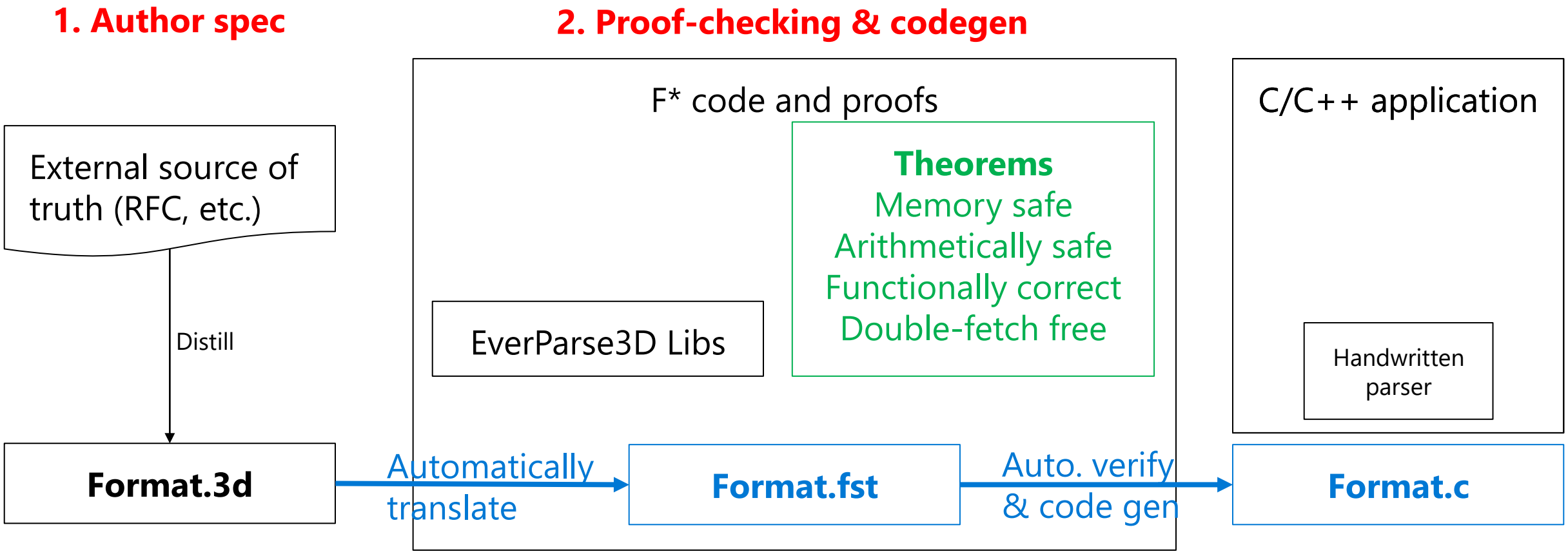

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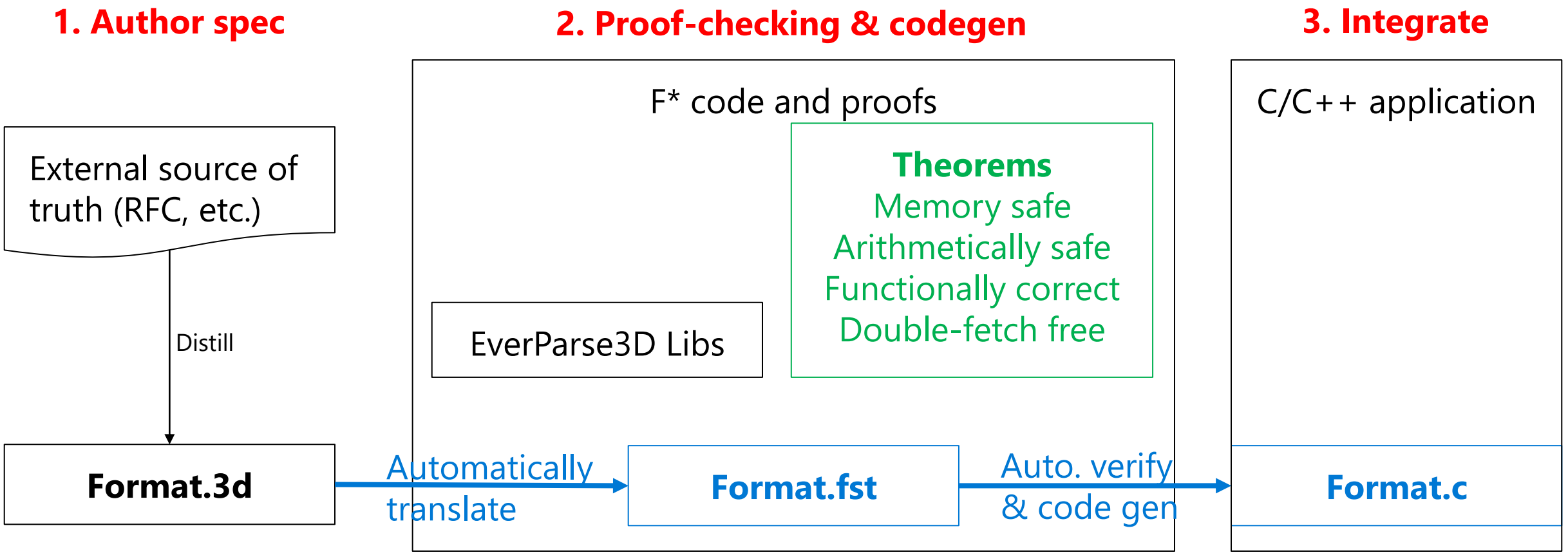

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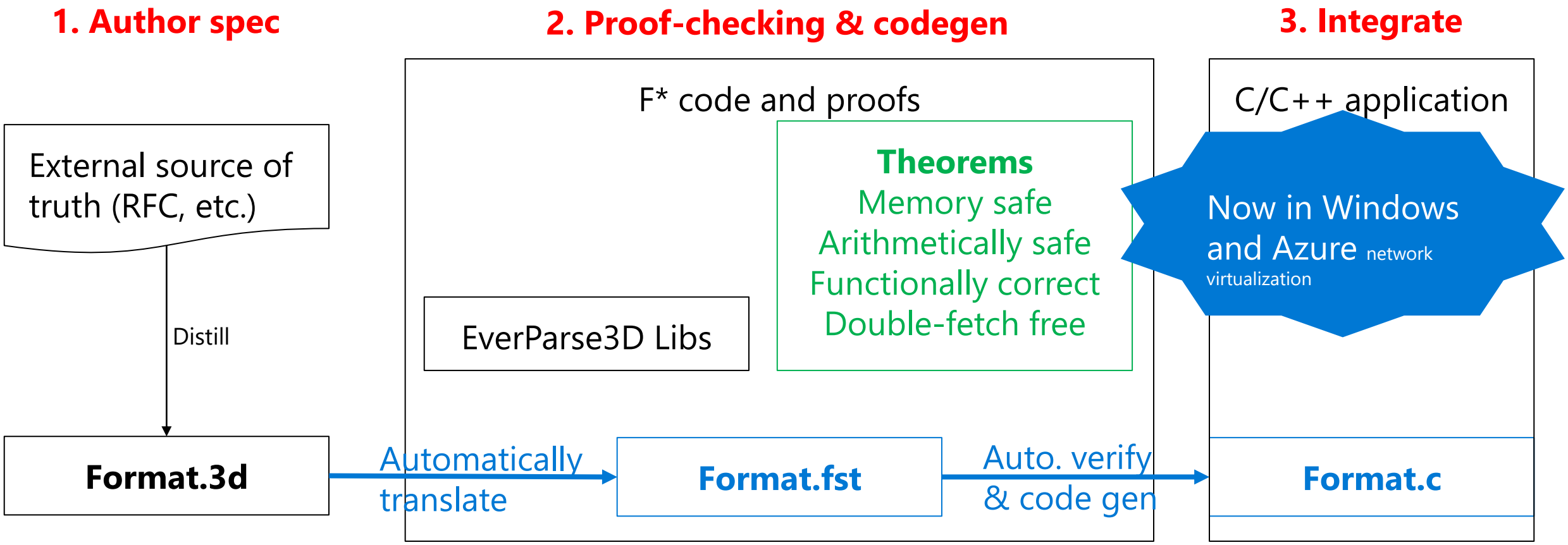

EverParse3D Guarantees

- Memory safety: no buffer overrun
- Arithmetic safety: no integer overflow

```
uint32_t fld_offset = input[current];
uint32_t fld = input[current+offset];
```

Missing checks for integer/buffer overflows

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- Functional correctness:
  - All ill-formed packets are rejected
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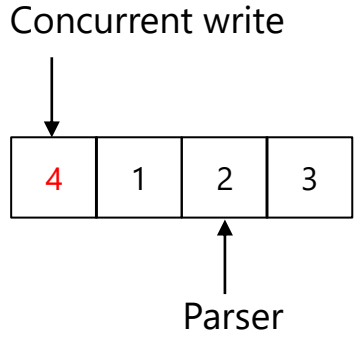
Missing checks for integer/buffer overflows

- Functional correctness:
  - All ill-formed packets are rejected
  - Every valid packet is accepted

- Double-fetch freedom: no “time-of-check to time-of-use” bugs
  - No exclusive read access to the input buffer
  - Solution: Read each byte at most once
  - Validation on a “logical snapshot” of the input data



3D: A source language of message formats for Dependent Data Descriptions

```
typedef struct _TCP_HEADER
{
  …
  UINT16 CWR:1;  UINT16 ECE:1;  UINT16 URG:1;  UINT16 ACK:1;
  UINT16 PSH:1;  UINT16 RST:1;  UINT16 SYN:1;  UINT16 FIN:1;  …
  URGENT_PTR UrgentPointer;


  OPTION          Options   [];
  UINT8           Data      [];
} TCP_HEADER;
```

```
typedef union _OPTION_PAYLOAD {


        all_zeros EndOfList;


        unit Noop;
      …
} OPTION_PAYLOAD;

typedef struct _OPTION {
    UINT8 OptionKind;
    OPTION_PAYLOAD
          OptionPayload;
} OPTION;
```

3D: A source language of message formats for Dependent Data Descriptions

Augmenting C data types with value constraints,

```
typedef struct _TCP_HEADER
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  UINT16 CWR:1;  UINT16 ECE:1;  UINT16 URG:1;  UINT16 ACK:1;
  UINT16 PSH:1;  UINT16 RST:1;  UINT16 SYN:1;  UINT16 FIN:1;  …
  URGENT_PTR UrgentPointer  {UrgentPointer == 0 || URG == 1 } ;


  OPTION          Options   [];
  UINT8           Data      [];
} TCP_HEADER;
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3D: A source language of message formats for Dependent Data Descriptions

Augmenting C data types with value constraints, variable-length structures

```
typedef struct _TCP_HEADER(UINT32 SegmentLength)
{
  …
  UINT16 CWR:1;  UINT16 ECE:1;  UINT16 URG:1;  UINT16 ACK:1;
  UINT16 PSH:1;  UINT16 RST:1;  UINT16 SYN:1;  UINT16 FIN:1;  …
  URGENT_PTR UrgentPointer  {UrgentPointer == 0 || URG == 1 } ;


  OPTION          Options    [:byte-size (DataOffset * 4) - sizeof(this)];
  UINT8           Data       [SegmentLength - (DataOffset * 4)];
} TCP_HEADER;
```

```
typedef union _OPTION_PAYLOAD {

        all_zeros EndOfList;

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typedef struct _OPTION {
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3D: A source language of message formats for Dependent Data Descriptions

Augmenting C data types with value constraints, variable-length structures, value-dependent unions

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  URGENT_PTR UrgentPointer  {UrgentPointer == 0 || URG == 1 } ;


  OPTION(SYN==1)  Options   [:byte-size (DataOffset * 4) - sizeof(this)];
  UINT8           Data      [SegmentLength - (DataOffset * 4)];
} TCP_HEADER;
```

```
casetype _OPTION_PAYLOAD
  (UINT8 OptionKind, Bool MaxSegSizeAllowed) {
  switch(OptionKind)  {
     case OPTION_KIND_END_OF_OPTION_LIST:
       all_zeros EndOfList;
     case OPTION_KIND_NO_OPERATION:
       unit Noop;
     …
}} OPTION_PAYLOAD;

typedef struct _OPTION(Bool MaxSegSize) {
    UINT8 OptionKind;
    OPTION_PAYLOAD(OptionKind, MaxSegSize)
          OptionPayload;
} OPTION;
```

3D: A source language of message formats for Dependent Data Descriptions

Augmenting C data types with value constraints, variable-length structures, value-dependent unions and actions

```
typedef struct _TCP_HEADER(UINT32 SegmentLength, mutable URGENT_PTR *Dst)
{
  …
  UINT16 CWR:1;  UINT16 ECE:1;  UINT16 URG:1;  UINT16 ACK:1;
  UINT16 PSH:1;  UINT16 RST:1;  UINT16 SYN:1;  UINT16 FIN:1;  …
  URGENT_PTR UrgentPointer  {UrgentPointer == 0 || URG == 1 }
                            {:on-success *Dst = UrgentPointer; };

  OPTION(SYN==1)  Options   [:byte-size (DataOffset * 4) - sizeof(this)];
  UINT8           Data      [SegmentLength - (DataOffset * 4)];
} TCP_HEADER;
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3D: A source language of message formats for Dependent Data Descriptions

Also in the paper:

- Full formalization of the language in F*
- 3 denotational semantics of a hybrid shallow-deep embedding
- Built on top of dependently-typed monadic parsing combinators (USENIX 2019)
- Via partial evaluation and 1st Futamura projection
- Yields high-performance C code via Karamel F*-to-C compiler (ICFP 2017)

```
  UINT8           Data      [SegmentLength - (DataOffset * 4)];
} TCP_HEADER;
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typedef struct _OPTION(Bool MaxSegSize) {
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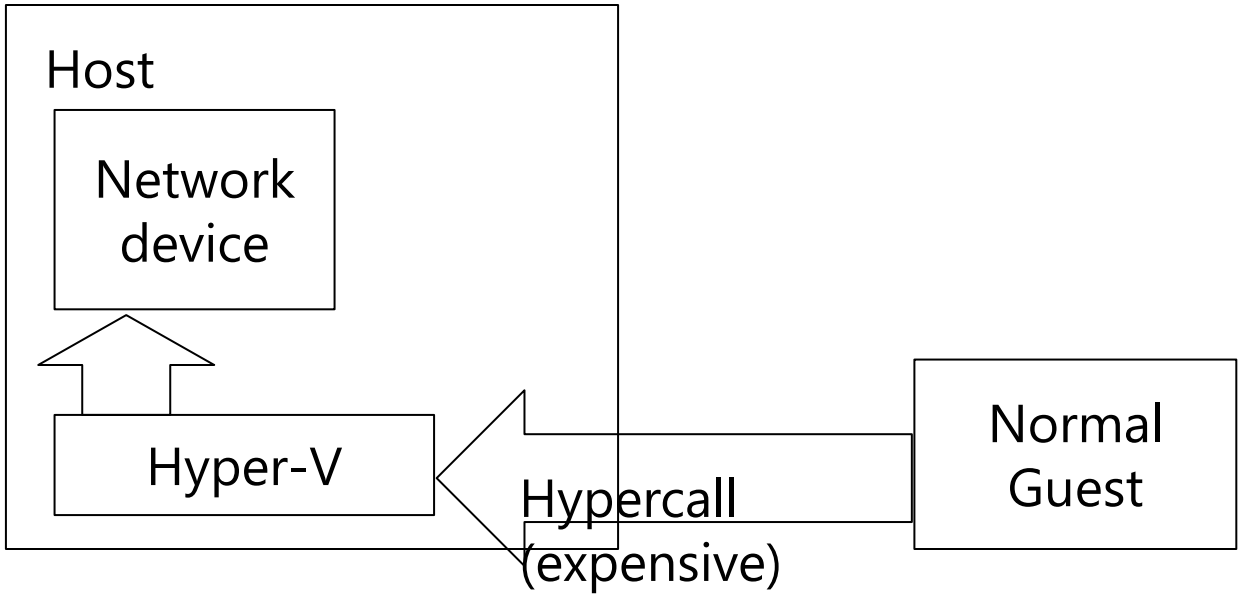
This paper: Verified Secure Parsers for Microsoft Hyper-V Network Virtualization

- Hyper-V: Hypervisor for Windows 10, 11, and all Azure Cloud

- vSwitch: Dispatches network packets from/to guests



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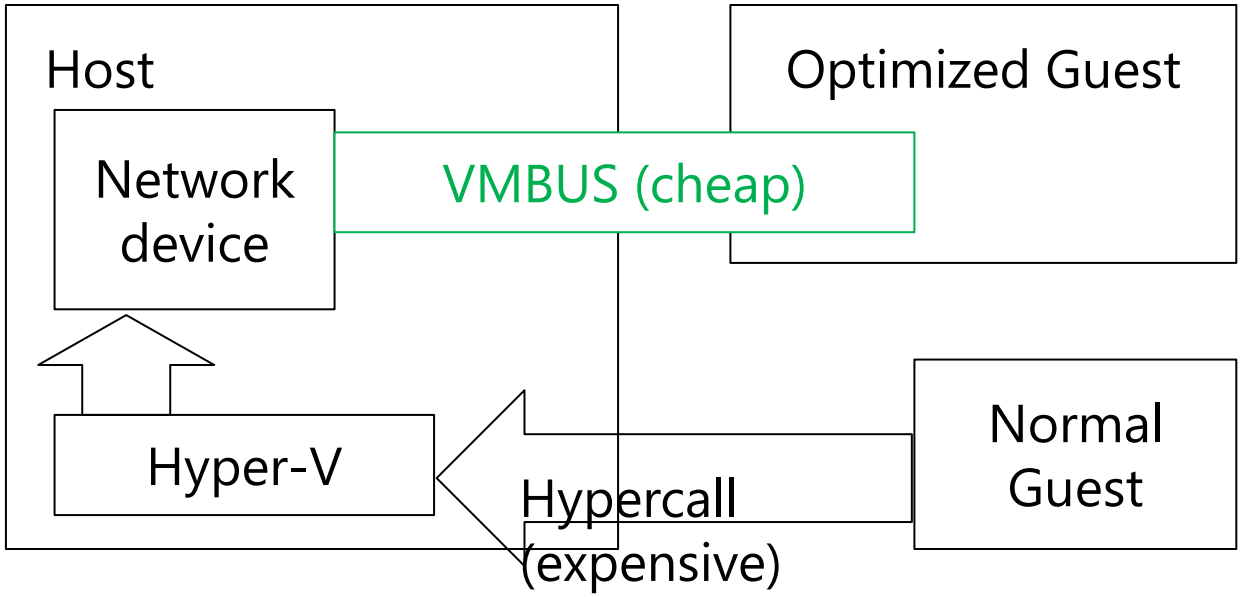
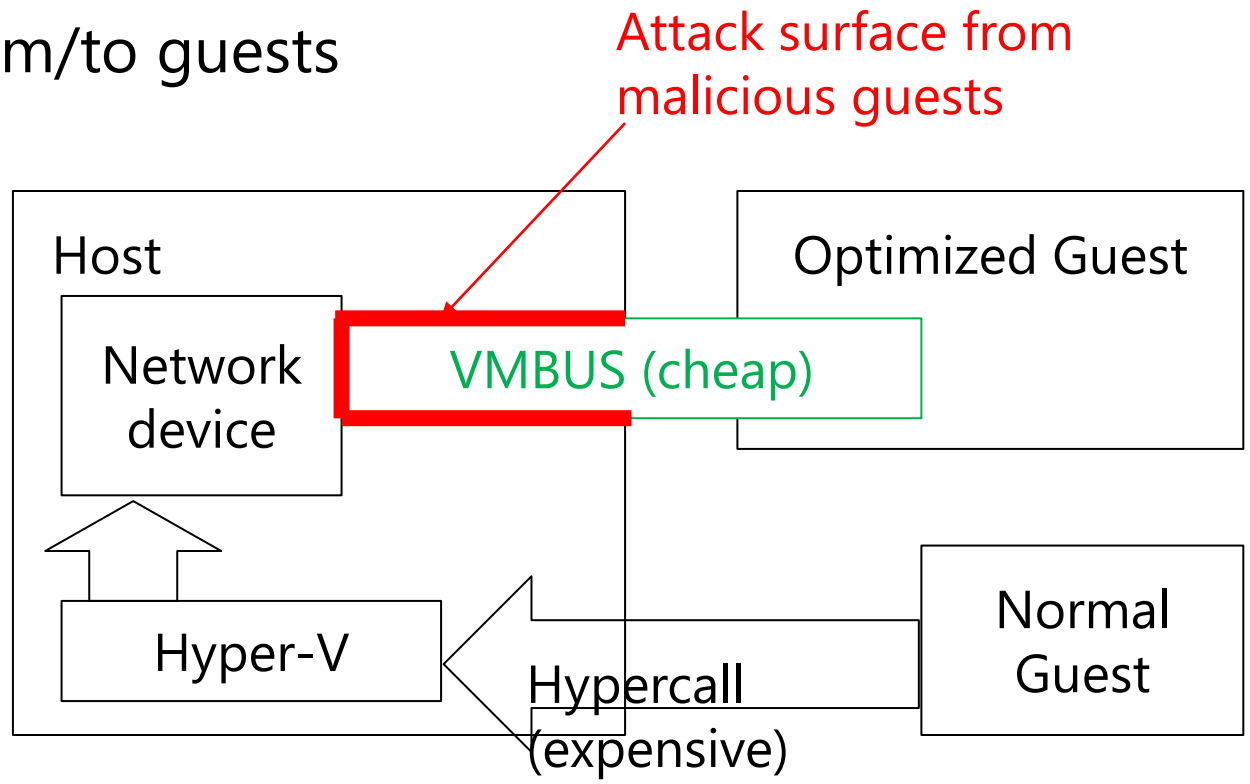
- Some guest-side optimizations to give some direct hardware access (VMBUS), bypassing a hypercall

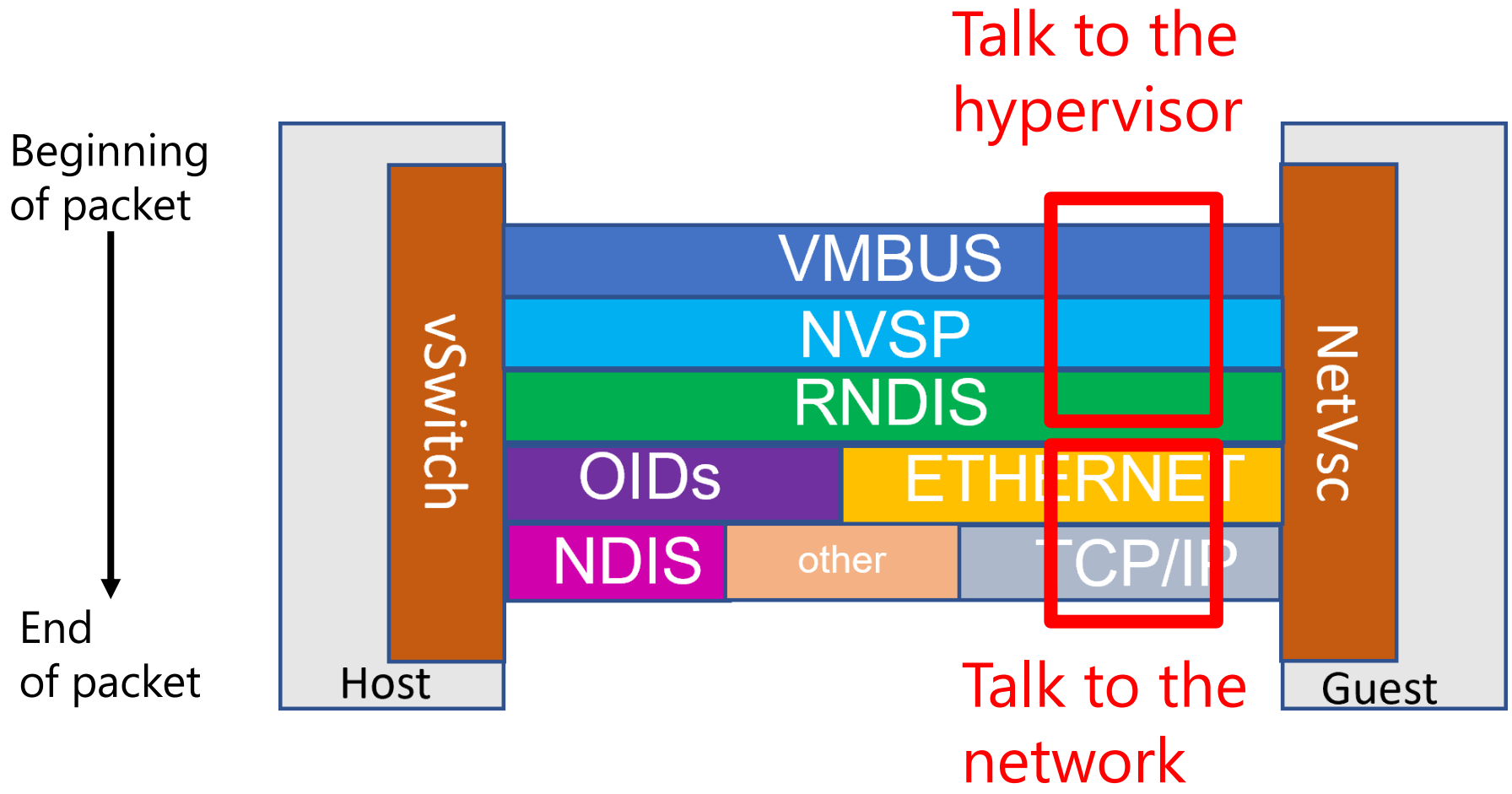


This paper: Verified Secure Parsers for Microsoft Hyper-V Network Virtualization

- Hyper-V: Hypervisor for Windows 10, 11, and all Azure Cloud
- vSwitch: Dispatches network packets from/to guests
- Some guest-side optimizations to give some direct hardware access (VMBUS), bypassing a hypercall
- Need to protect against attacks from network or malicious guests crafting ill-formed packets to break isolation / gain host access



Hyper-V vSwitch: network packet layers



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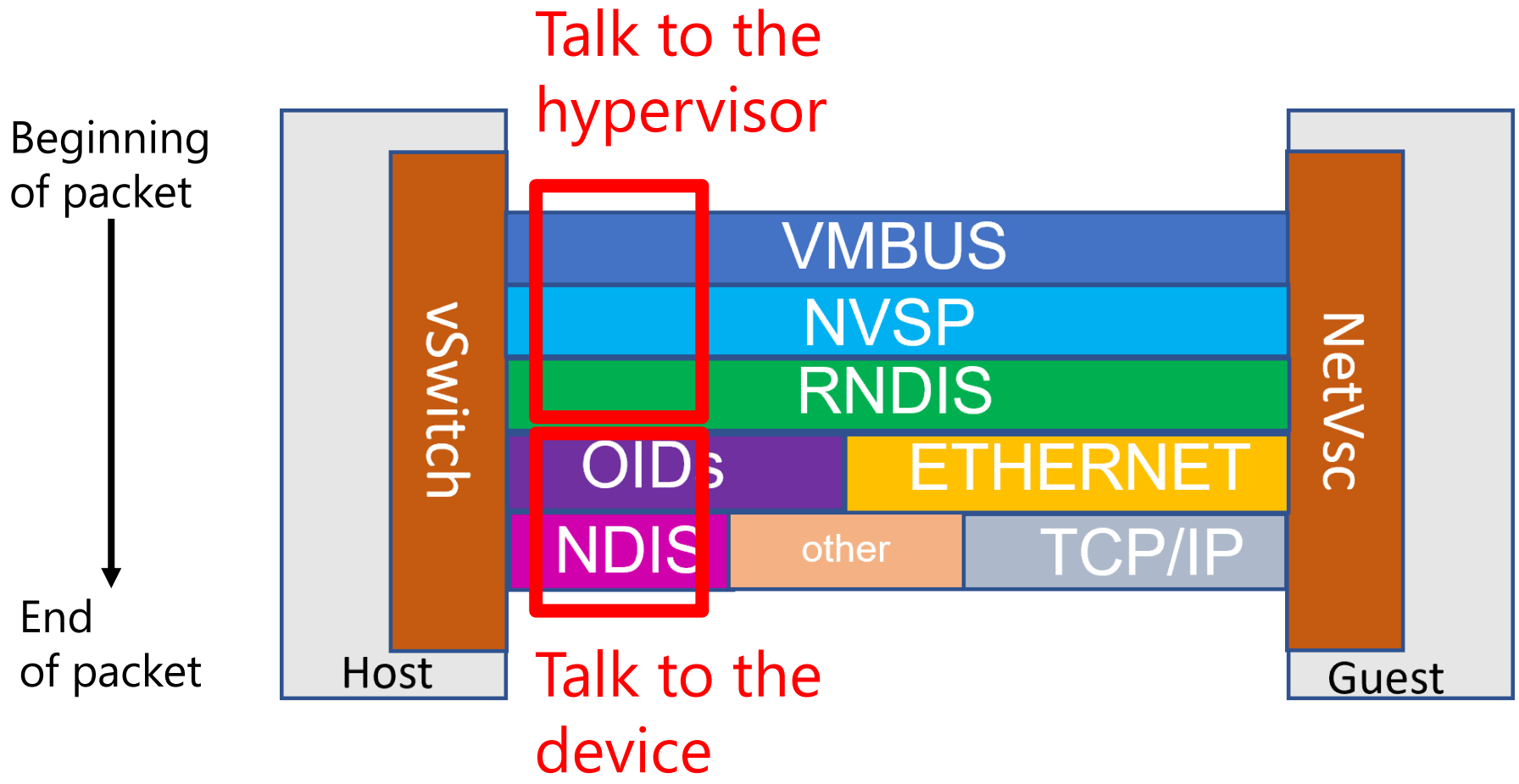
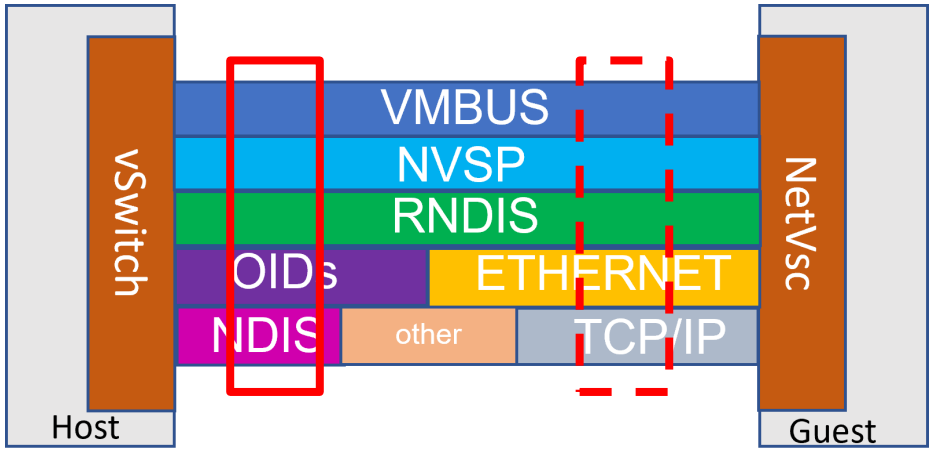


Hyper-V vSwitch with EverParse3D

- **Now in Windows 10, 11, and Azure Cloud**: Every network packet passing through Hyper-V is validated by EverParse3D formally verified code

- NVSP, RNDIS, OIDs and NDIS
  - Some of which are proprietary
  - Other formats (TCP, etc.) in progress
- 5K lines of 3D specification
  - 137 structs, 22 casetypes, 30 enum types
- Verified in 82 s
- Generated 23K C code



Performance

Generated code is fast…

- Our code passed internal performance regression testing, imposing **less than 2% cycles/byte** overhead
- In some cases, our code is more efficient by virtue of eliminating unneeded copies

… thanks to careful design

- Validators operate in-place
- Validators only read data at most once: client code no longer needs to copy data before validating it
- Layered specifications + one single pass = fail early

Detailed performance results contain proprietary information, thus are not included in the paper

A multi-year (since summer 2019), multi-org effort

Research Team

Product Team

Testing Team

Security Team

A multi-year, multi-org effort

Research Team Product Team

Gather requirements:

- Parsing actions
- Double-fetch freedom
- <2% perf overhead
- Generated C code quality (guidelines, etc.)

A multi-year, multi-org effort

Research Team Product Team

Figure out the data format specification:

- Some protocols have no pre-existing specs
- Backward compatibility

A multi-year, multi-org effort

Research Team Product Team Testing Team

Figure out the data format specification:

- Some protocols have no pre-existing specs
- Backward compatibility
- Complex testing matrices

A multi-year, multi-org effort

Security Team

Security evaluation:

- Spec audited, security team wrote unit tests
- vSwitch code fuzzers stopped finding bugs:
  - Malformed packets properly rejected by our parsers
  - Helped refocus fuzzers to functionality fuzzing

A multi-year, multi-org effort

Research Team Product Team

Productivity improvements:

- EverParse3D now part of the Windows build environment (incl. Z3, F*, Karamel)
- Critical to meet product deadlines:
  - saves code writing cost
  - more focused security reviews

A multi-year, multi-org effort

+ Other teams (servicing, etc.)

Product Team Testing Team Security Team

Active Maintenance (2 years already):

- Product teams change the specs as they integrate new features
- Backport to older product versions
- Generated C code checked in the product repo to aid other teams' understanding

EverParse3D Takeaway

- A sweet spot for formal verification
  - Strong mathematical guarantees of memory safety and functional correctness
  - Provably correct by construction: Zero user proof effort
  - High-performance code generated from data format description in a high-level declarative language
  - High return on investment wrt. attack surface
- Project page and manual: https://project-everest.github.io/everparse/
  - Open-source (Apache 2 license)
  - Binary releases for Linux and Windows