Designing a Secure and Space-Efficient Executable File Format for the Unified Extensible Firmware Interface

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2nd August 2023

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Outline

1. Introduction to UEFI and Images
2. Image File Format Design
   - Compressed Encoding Techniques
   - Enforcing Constraints via Compressed Encoding
3. Implementations
   - Image File Format Conversion
   - Intermediate Representation
   - Functional and Safety Analyses
4. Evaluation

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Introduction and Problem Statement

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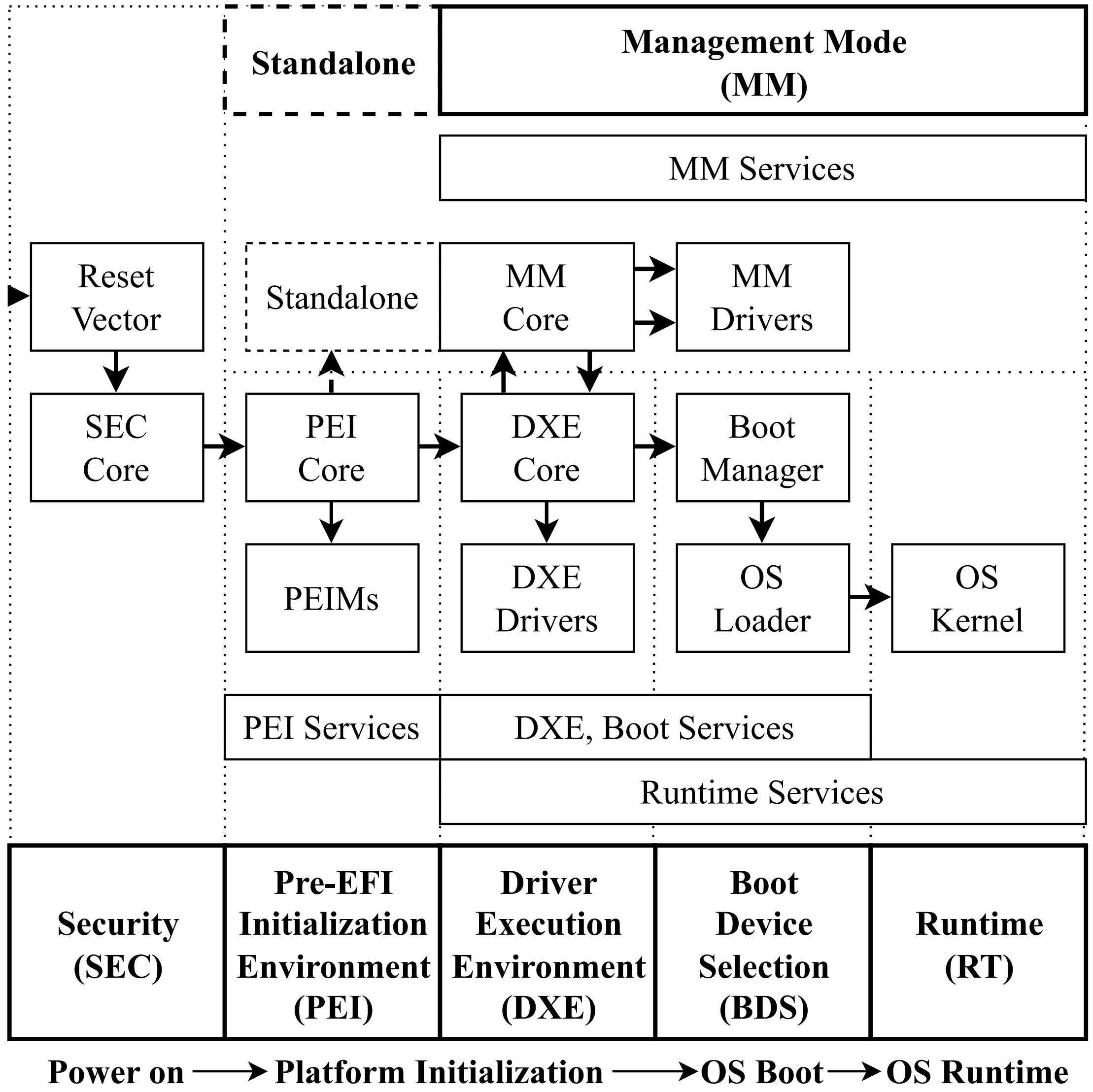
UEFI PI and UEFI

- Unified Extensible Firmware Interface (UEFI) is the de-facto standard boot specification for many private and corporate devices (x86, Qualcomm, …)
- UEFI Platform Initialization (UEFI PI) is the de-facto standard hardware initialization specification for x86 devices
- Both started replacing x86 BIOS at a scale in the early 2010s
- All known widespread implementations are based on TianoCore EDK II
- Support for several security technologies like Secure Boot

UEFI PI and UEFI (Cont'd)



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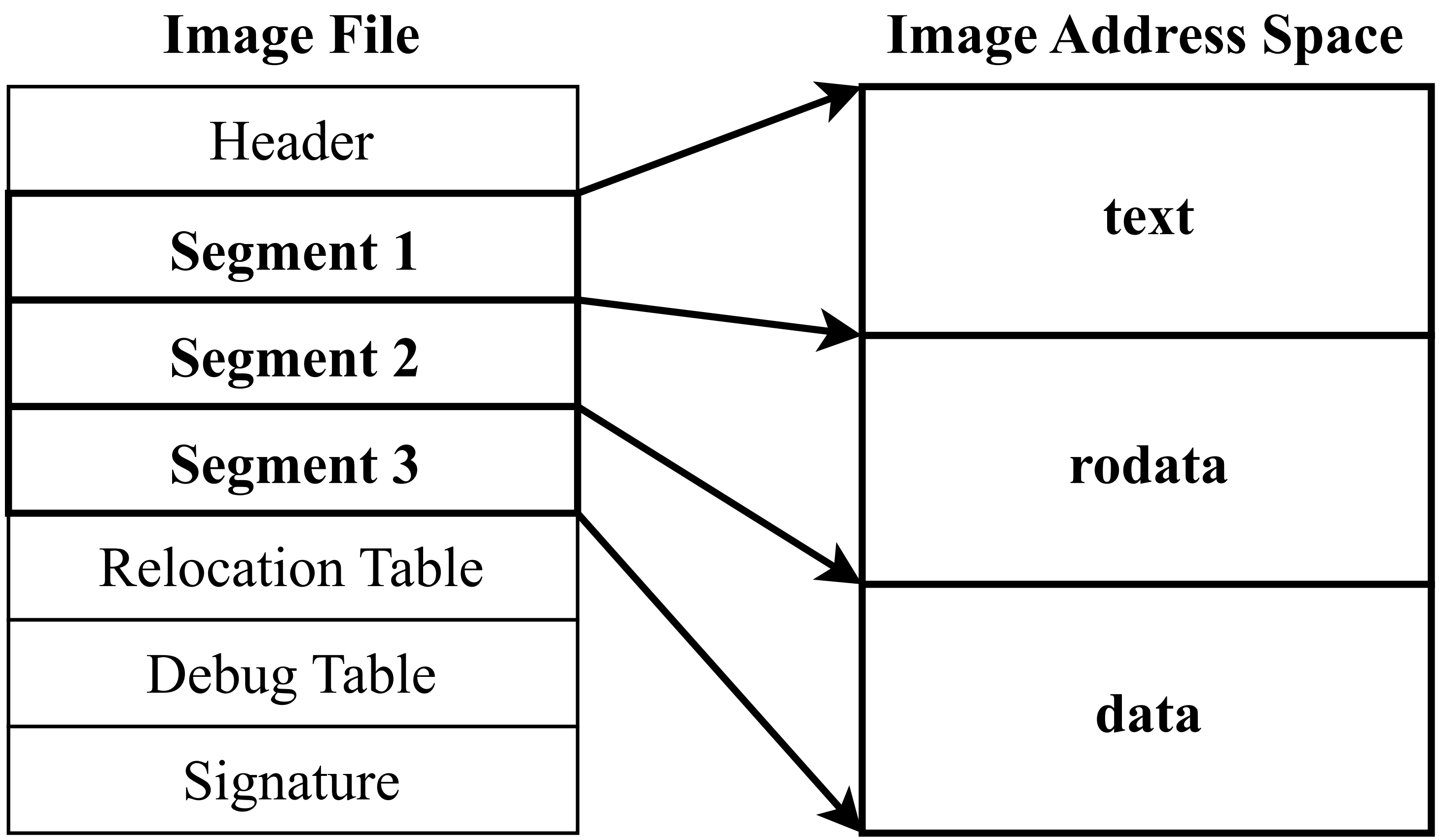
Abstraction of UEFI Images



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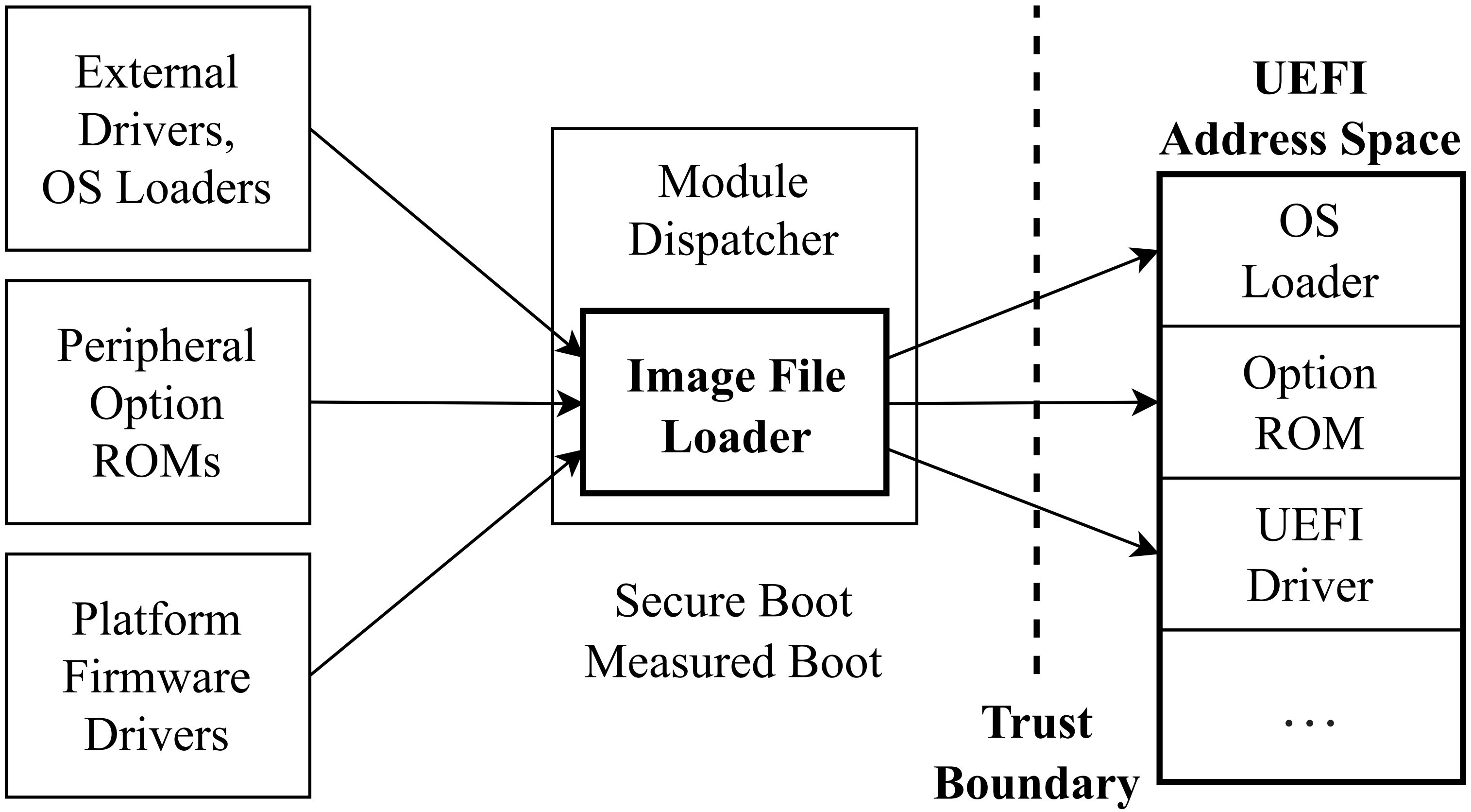
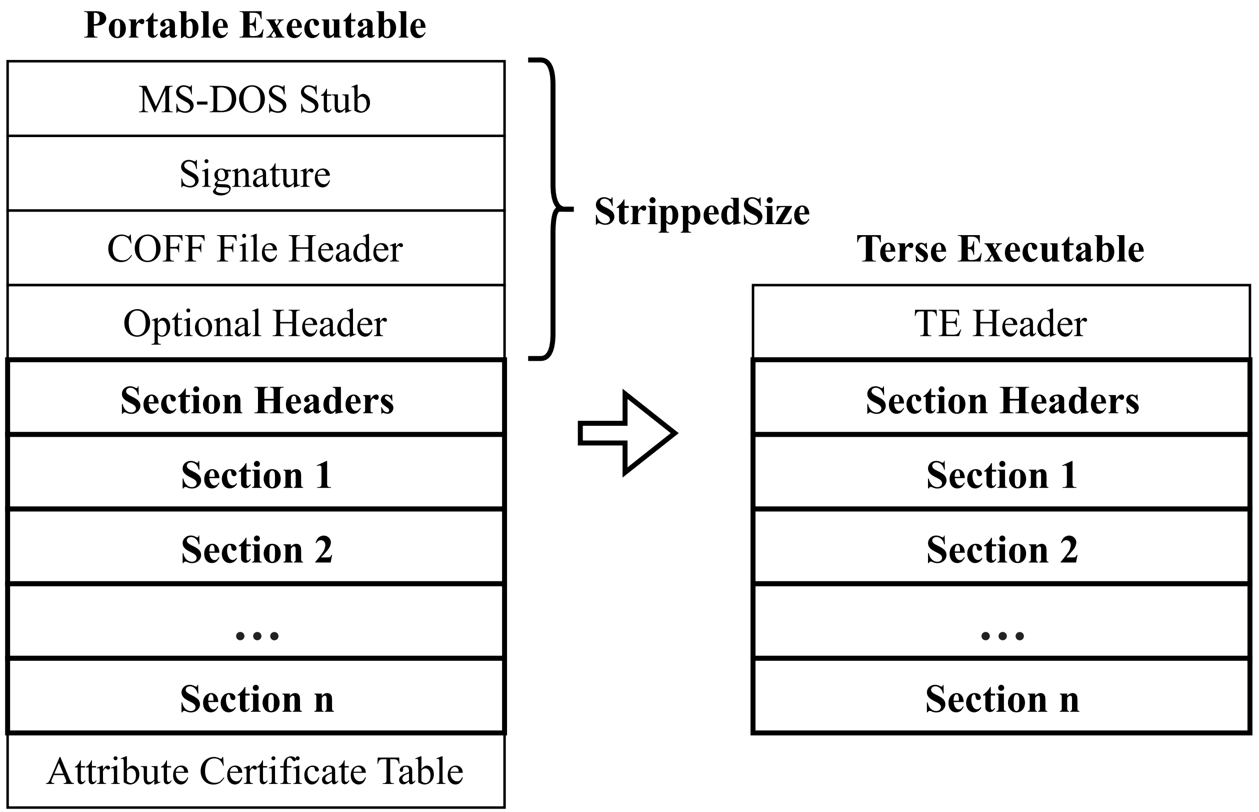
UEFI Image File Loader



UEFI PI Terse Executable File Format



Shifted file offsets are not fixed up!

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Problem Statement

- PE headers are complicated and carry a lot of legacy burden
  - Hard to construct and parse correctly (see real-world bugs)
  - Waste space with unused data (e.g. DOS header)
- UEFI features only few of modern OS security techniques
- Firmware storage generally is very limited → TE format
- Various real-world bugs with the current parsing and generation stacks

→ **Goal**: Design a new stack for firmware internals

- Easy-to-parse and space-efficient UEFI executable file format
- Sophisticated and self-validating image file format conversion

Image File Format Design

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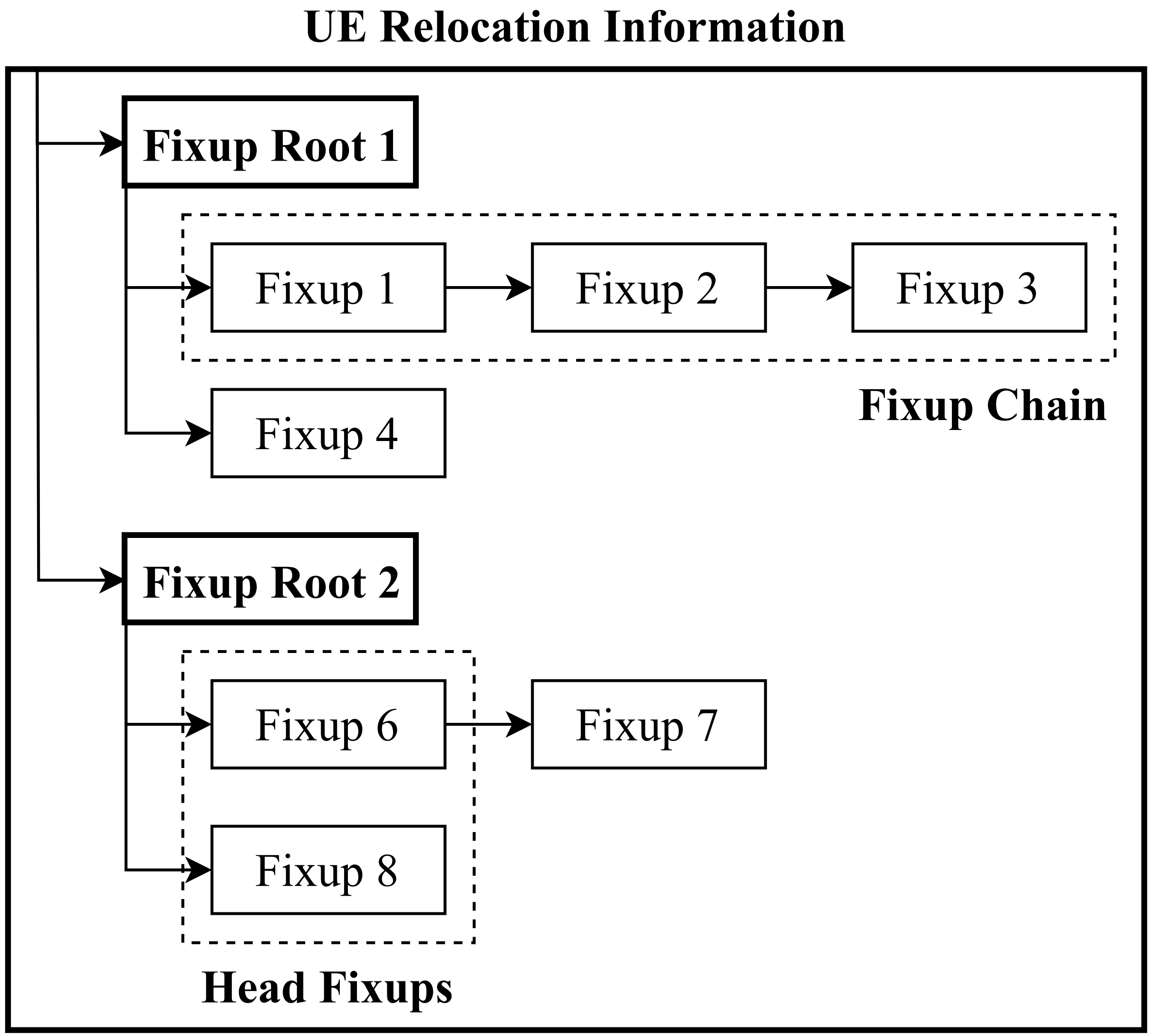
UEFI Executable File Format

- Limited scope:
    - No support for static or dynamic linking
    - No support for features relying on virtual memory
    - Tailored to UEFI PI and UEFI designs and use cases
- Simple design to enable easy and secure parsing
- Compressed encoding techniques to help with firmware storage constraints
- Unstable design for firmware-internal use

Relocation Fixup Hierarchy



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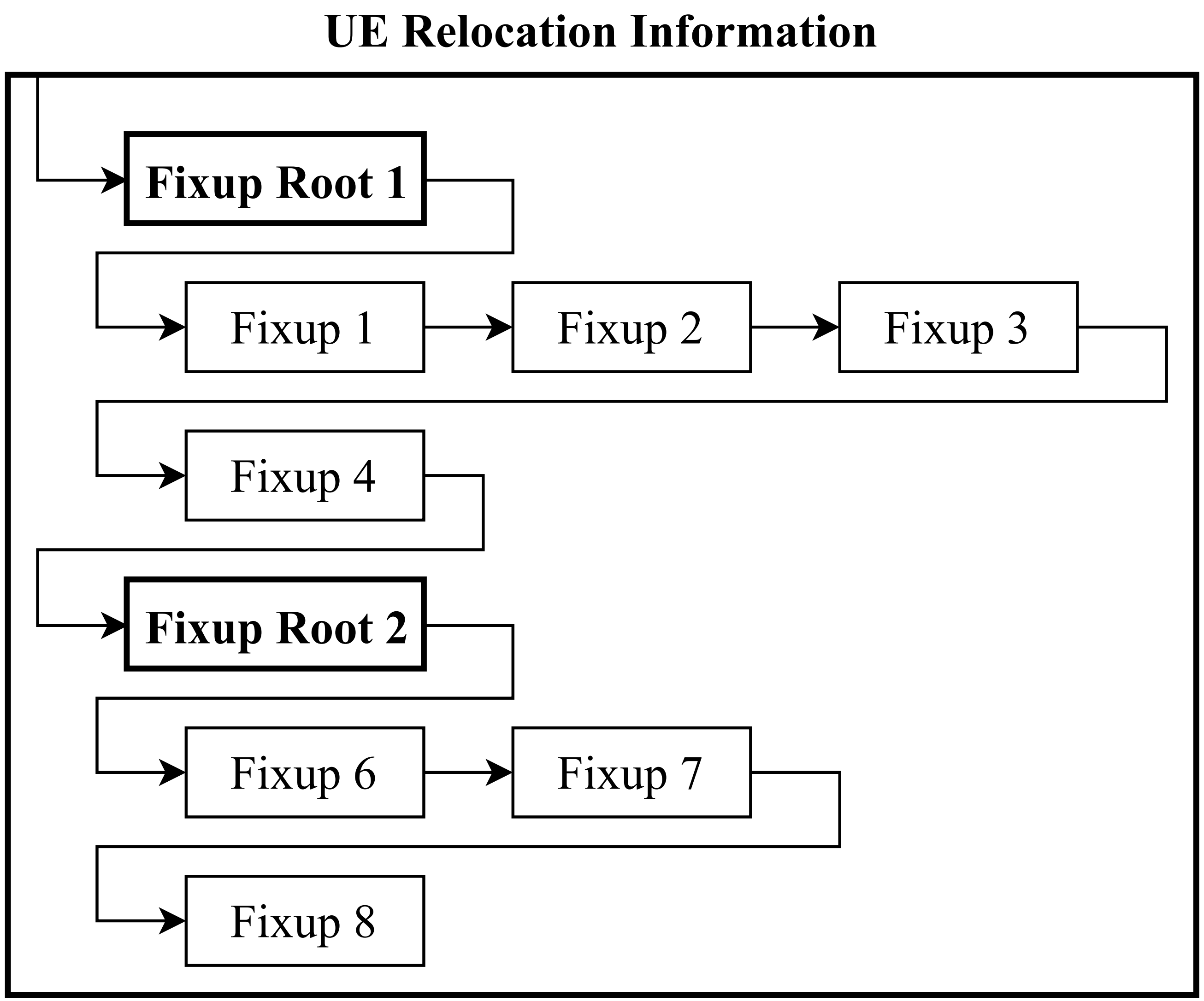
Relocation Fixups: Delta Encoding



Relocation Fixups: Delta Encoding (Cont’d)

- Noteworthy space-savings (in firmware storage terms):
    - Only fixup roots use full 32-bit offsets, head fixups use 16-bit offsets
    - Chained fixups store all metadata at the target → no size overhead
- But also, strong guarantees by the encoding:
    - Disjoint targets
    - Ordered ascending
- Can aid formalization efforts
- Particularly slow random access, but there is no UEFI use case

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Effects of Compressed Encoding

Compressed Encoding

Space Savings

Considered overengineering

Decoding Constraints

Interesting side effect

Enforcing Constraints via Compressed Encoding

- `encode(x)`: Valid Values → Encoded Values
- `decode(x)`: Encoded Values → Decodable Values
- May be well-defined for larger (co-)domains, but output may be nonsense
- If `encode` and `decode` are bijections, Decodable Values = Valid Values
    - Invalid values simply cannot be encoded
    - No runtime checks for validity necessary

Example 1: Data Alignment Requirements

- Data alignment requirements must be a power of two
  - Basic data types: Commonly ‘natural alignment’ (i.e. size = alignment)
  - Image segments: Commonly platform page size (min. 4 KiB for UEFI)
- Idea:
  - For data alignment requirements, encode as $\mathrm{log}_2(\mathrm{x})$
  - For aligned values, encode as $\mathrm{x}\ /\ \mathrm{a}$

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Example 2: Memory Permissions

1. none
2. read
3. write
4. execute
5. read, write
6. read, execute
7. write, execute
8. read, write, execute

Memory permissions are typically encoded with a bitmask.

Example 2: Memory Permissions

1. none
2. read
3. write
4. execute
5. read, write
6. read, execute
7. ~~**write, execute**~~
8. ~~**read, write, execute**~~

1. Eliminate violations of the W^X rule.

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Example 2: Memory Permissions (Cont'd)

1. ~~**none**~~
2. read
3. ~~**write**~~
4. execute
5. read, write
6. read, execute
7. ~~write, execute~~
8. ~~read, write, execute~~

1. Eliminate violations of the W^X rule.
2. **Eliminate unhelpful configurations.**

Example 2: Memory Permissions (Cont’d)

1. read
2. execute
3. read, write
4. read, execute

We are left with a power of two → encode as enumeration.

Implementations

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Image File Parsing and Format Conversion

- Existing parsing libraries are tailored to their format
  - Different API design
  - Burden on the caller to support all libraries
- Generate UE files from ELF, Mach-O, and PE files
- Existing conversion solutions translate directly
  - Requires separate translation logic for each input-output pair
  - No output correctness validation

→ **Idea**: Leverage image abstraction for both
  - Generic UEFI image parsing library API following abstraction
  - Conversion via an intermediate representation following abstraction

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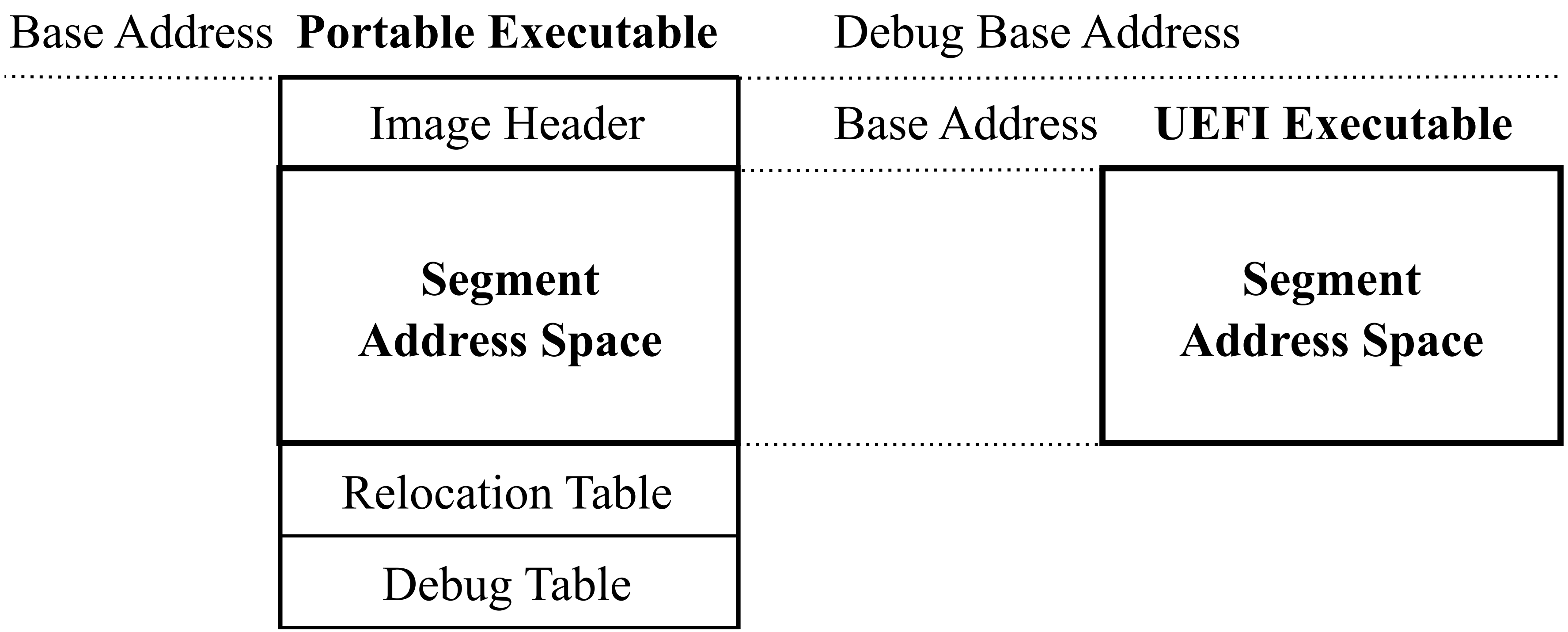
Caveat: PE Implicit File Header Loading



Store the delta in the header.

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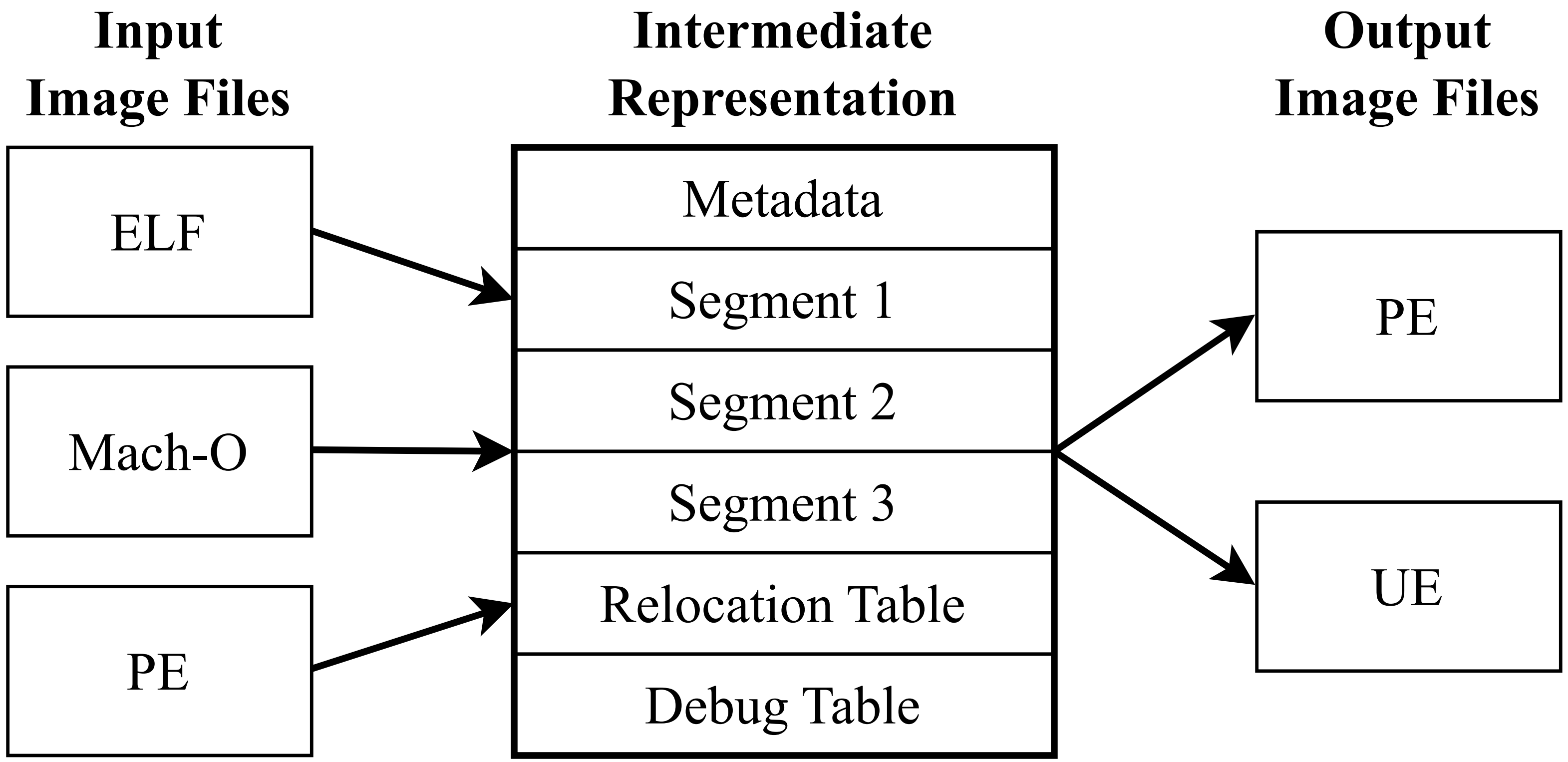
UEFI Image Intermediate Representation



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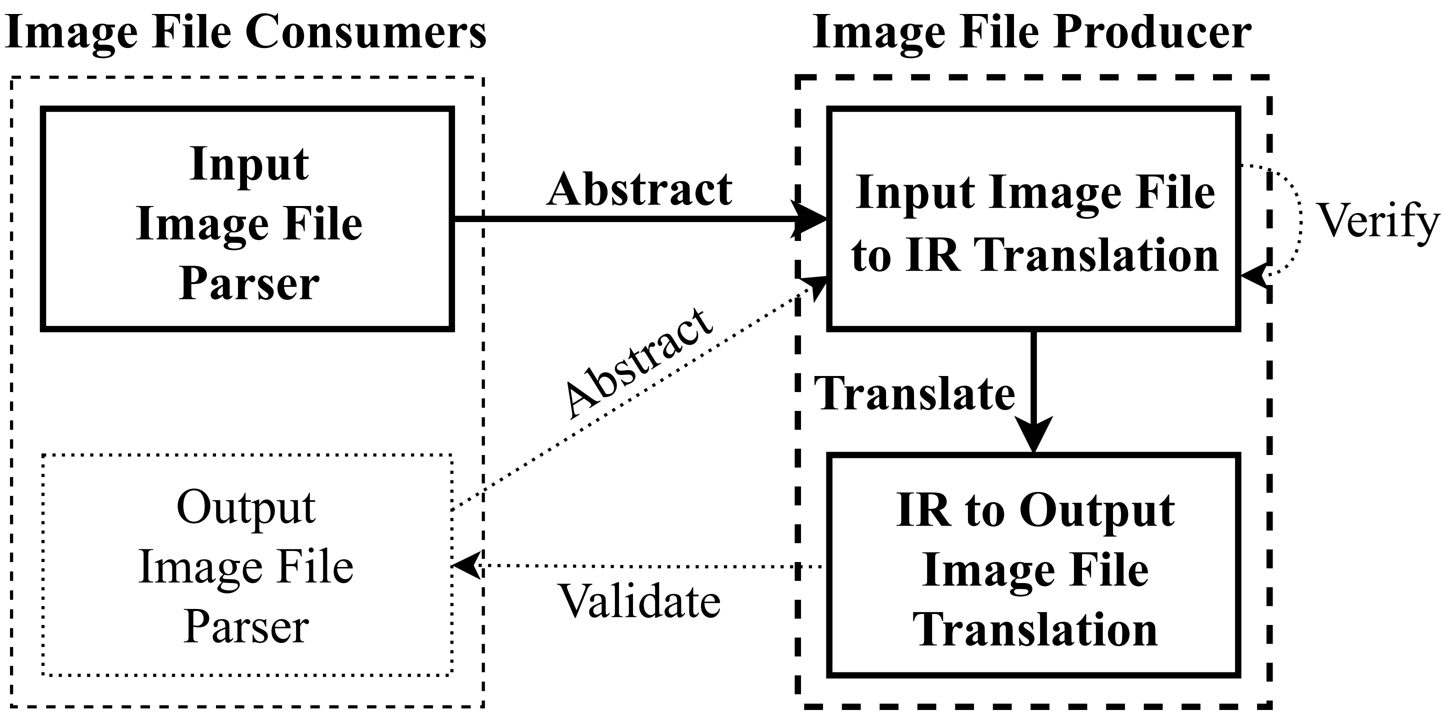
UEFI Image Intermediate Representation (Cont’d)

- Based on our UEFI image abstraction
- Semi-canonical definition
  - Most metadata are trivially canonical
  - Segments and reloc fixups are ordered ascending by address
  - Due to format-specific limitations, segment names may be truncated
- Can be used to compare conversion input and output
  - Almost all data are checked for equality
  - Segment names are prefix-matched

UEFI Image Conversion Stack



Functional and Safety Analyses

- Conversion equivalence checking
- Using EDK II parsing libraries to keep requirements in-sync
- Static Analysis using Clang Static Analyzer, GitHub CodeQL, and Coverity
- Fuzz-Testing of the EDK II parser and the conversion using LLVM libFuzzer
    - Functionality testing due to conversion equivalence check
    - Safety testing using LLVM ASan and UBSan
- Automated boot testing using UEFI Shell, Linux, and Windows environments

Evaluation and Conclusion

- All static analysis reports on main components were resolved
- Fuzz-testing slowed down corpus evolution after two weeks
  → Best-effort functional and safety validation
- 9.7 % avg. space saving per module, up to 78 KiB total for X64 OVMF
  → Evolutionary space efficiency improvements
- Visibly smaller parsing library compared to PE
- All artifacts were publicly released and all tests were run by GitHub CI

→ The task was solved, but only a first step towards simplifying booting

Thank You!

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