Verifying Firmware for Confidential Computing with CPAchecker (Work in Progress)

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Confidential Computing

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- Threats of data breaches

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How can we protect data when they are in use, especially in a remote execution environment, e.g., cloud?

Using Trusted Execution Environment to Protect Data in Use

- Intel Trust Domain Extensions (TDX) [1]
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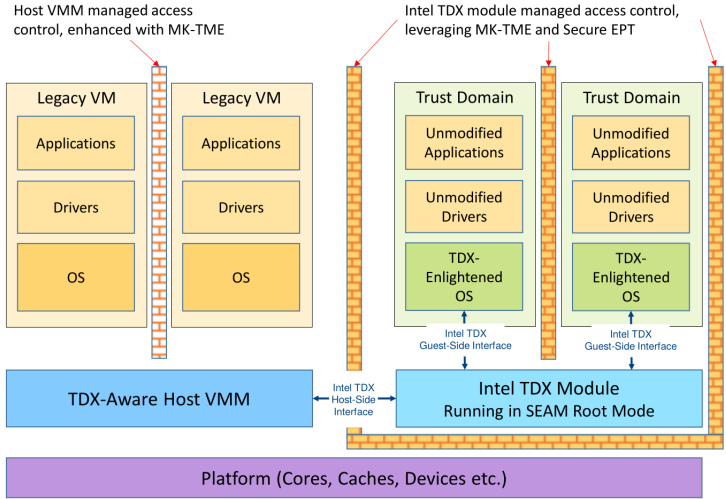
- Similar techniques
  - ARM Confidential Compute Architecture [2, 3, 4]
  - AMD Infinity Guard [5]

Intel TDX: Overview



Source: Figure 2.1 in Intel TDX Module v1.5 Base Architecture Specification

Intel TDX: Components

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  - TD: accept a new page, read global metadata of a TDX module, etc.

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Goal: verify ABIs of TDX module (implemented as C code plus assembly), assuming VMM and TDs can call any ABI with any inputs

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Work in progress: create a benchmark set of TDX verification tasks for functional correctness (w.r.t. SV-COMP rules)

Intel TDX: Specification for ABI Function `TDG.SYS.RD`

Table 5.324: TDG.SYS.RD Input Operands Definition

Operand	Description		
RAX	TDCALL instruction leaf number and version, see 5.4.1		
	Bits	**Field**	**Description**
	15:0	Leaf Number	Selects the TDCALL interface function
	23:16	Version Number	Selects the TDCALL interface function version Must be 0
	63:24	Reserved	Must be 0
RDX	Field identifier – see 3.10 The LAST_ELEMENT_IN_FIELD and LAST_FIELD_IN_SEQUENCE components of the field identifier must be 0. WRITE_MASK_VALID, INC_SIZE, CONTEXT_CODE and ELEMENT_SIZE_CODE components of the field identifier are ignored. A value of -1 is a special case: it is not a valid field identifier; in this case the first readable field identifier is returned in RDX.		

Table 5.325: TDG.SYS.RD Output Operands Definition

Operand	Description
RAX	TDCALL instruction return code – see 5.4.1
RDX	If the input field identifier was -1, RDX returns the first readable field identifier. Else, in case of an error, RDX returns -1. On success, RDX returns the next readable field identifier. A value of -1 indicates no next field identifier is available.
R8	Contents of the field In case of no success, as indicated by RAX, R8 returns 0.
Other	Unmodified

Source: Intel TDX Module v1.5 ABI Specification

Firmware-Specific Constructs

- Byte/Bit-precise modeling of memory layouts
- Inline assembly
- Externally defined variables

Multiple Interpretations of Registers (Type Punning)

```
typedef union tdx_leaf_and_version_u {
  struct {
    uint64_t leaf : 16;
    uint64_t version : 8;
    uint64_t reserved0 : 8;
    uint64_t reserved1 : 32;
  };
  uint64_t raw;
} tdx_leaf_and_version_t;
```

Multiple Interpretations of Registers (Type Punning)

```c
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```c
typedef union md_field_id_u {
  struct {
    // Lower 32 bits
    union {
      struct {
        uint32_t field_code : 24;
        uint32_t reserved_0 : 8;
      };  // default field code
      struct {
        uint32_t element : 1;
        uint32_t subleaf : 7;
        ...
      } cpuid_field_code;
    };
    // Upper 32 bits
    struct {
      ...
    };
  };
  uint64_t raw;
} md_field_id_t;
```

Compiler Attributes for Memory Alignment

```c
// Size: 8 bytes
typedef struct Example_s {
  char c;
  int i;
} Example_t;

// Size: 5 bytes
typedef struct Example_packed_s {
  char c;
  int i;
} __attribute__((packed)) Example_packed_t;

// Size: 16 bytes
typedef struct Example_aligned_s {
  char c;
  int i __attribute__((aligned(8)));
} Example_aligned_t;
```

Example of Inline Assembly: Access Loader-Defined Variables

```
_STATIC_INLINE_ tdx_module_local_t* get_local_data(void) {
  uint64_t local_data_addr;
  _ASM_("movq %%gs:%c[local_data], %0\n\t"
        : "=r"(local_data_addr)
        : [local_data] "i"(
            offsetof(tdx_module_local_t, local_data_fast_ref_ptr)));
  return (tdx_module_local_t*)local_data_addr;
}
```

Challenges for Software Verifiers

- Preliminary investigation on a few examples

FW constructs	CPAchecker [6]	Cbmc [7]
Type punning	Partially supported	Supported
Compiler attribute	Partially supported	Partially supported
Inline assembly	Unsupported	Partially supported
Variable defined externally	Error	Error

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- CPAchecker: large `enum` value, compiler attribute, static assertion, anonymous `union`/`struct`
- Cbmc: nested compiler attributes

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Hardware modeling (e.g., inline assembly) is verifier-agnostic: avoid reinventing the wheel in every verifier by program transformation [8]

Modeling Inline Assembly via Program Instrumentation

```
_STATIC_INLINE_ tdx_module_local_t* get_local_data(void) {
#ifdef TDXFV_NO_ASM
  return &local_data_fv;
#else
  uint64_t local_data_addr;
  _ASM_("movq %%gs:%c[local_data], %0\n\t"
        : "=r"(local_data_addr)
        : [local_data] "i"(
            offsetof(tdx_module_local_t, local_data_fast_ref_ptr)));
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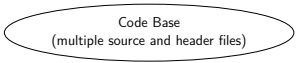
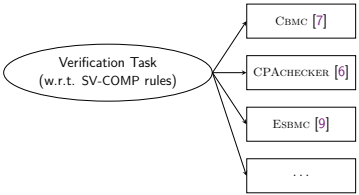
- Desired: `__VERIFIER_nondet_struct_X()` for initializing an arbitrary struct

Bridging Industrial Code Base and Academic Software Verifiers by Program Transformation





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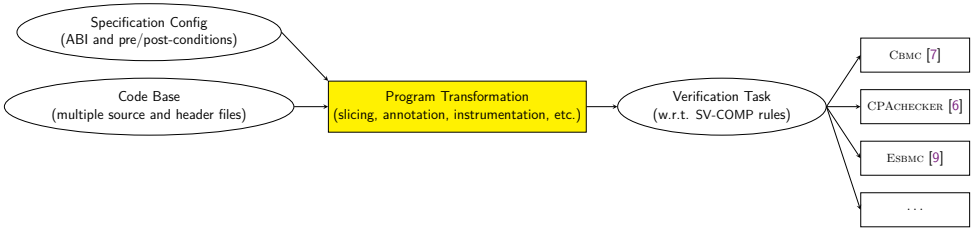

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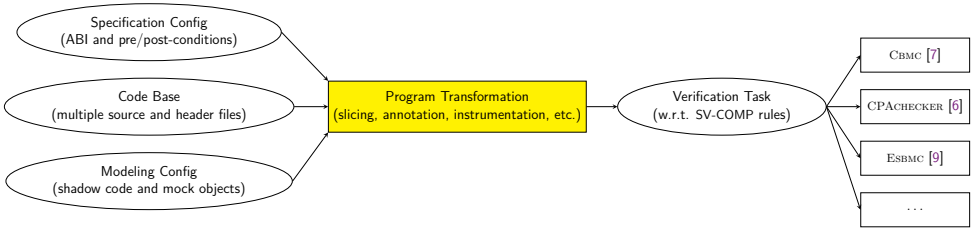

- Slice off irrelevant code
- Annotate pre/post-conditions
- Instrument shadow C code to model inline assembly

Firmware Verification: What We Have Learned So Far

- Manage and communicate with hardware
  - Data structure
    - Byte/Bit-precise and polymorphic types to simulate register/memory layouts
    - No dynamic allocation
  - Operation
    - Inline assembly to call instructions $\rightarrow$ hardware modeling (manually)
    - More data movement and less arithmetic
    - Statically-sized loops $\rightarrow$ BMC (but bounds are high)

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- Transformation as a way to bridge gaps and unify knowledge [8]
- Working with industry

References I

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