Static Analysis Based Invariant Detection for Commodity Operating Systems

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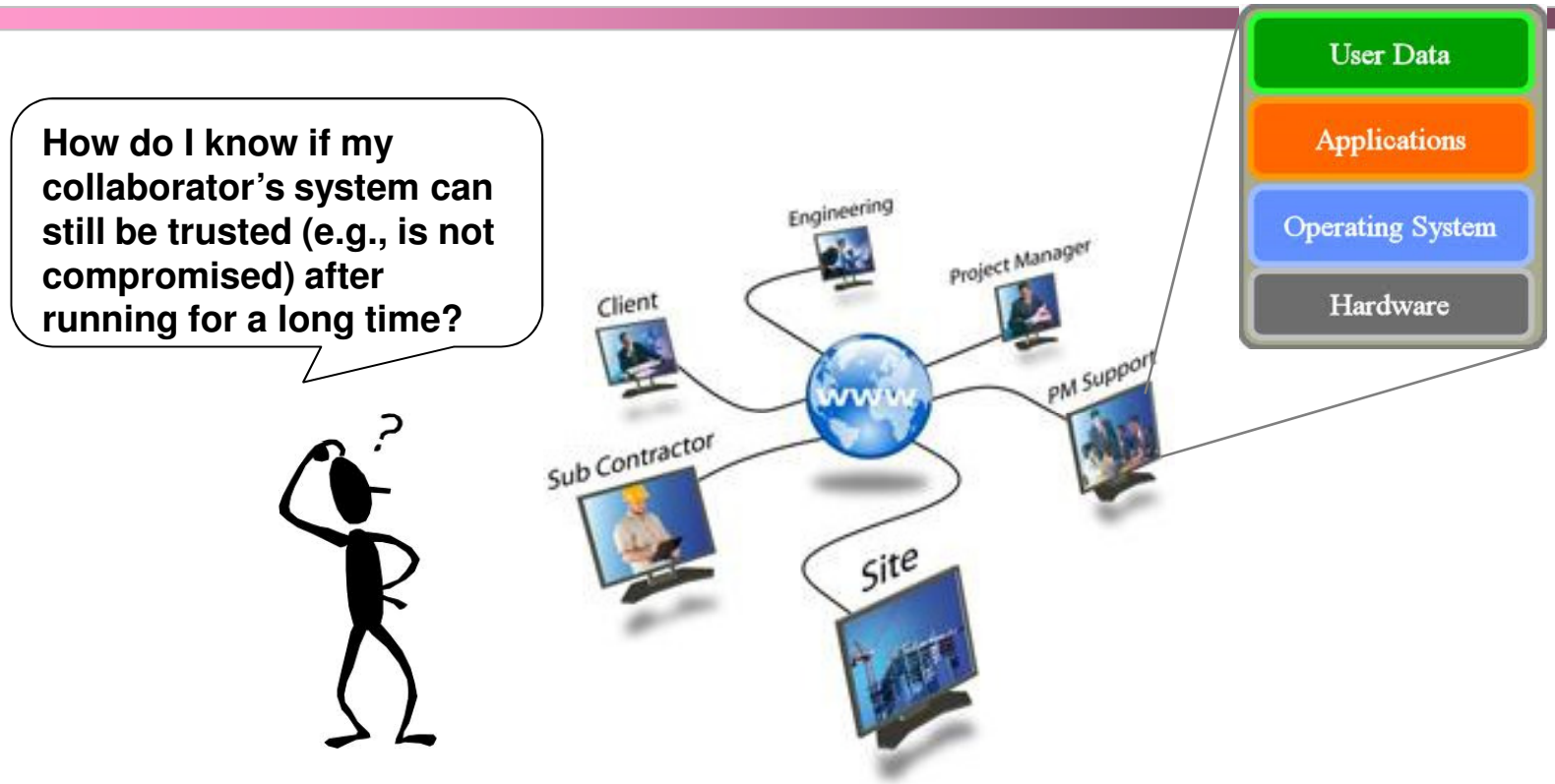
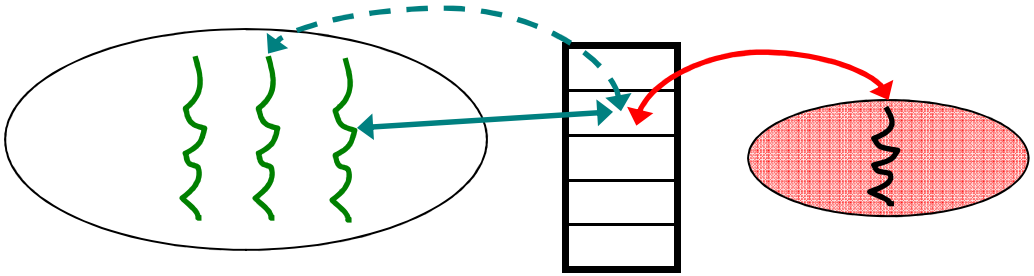
Trust Issues in Collaborative Environments



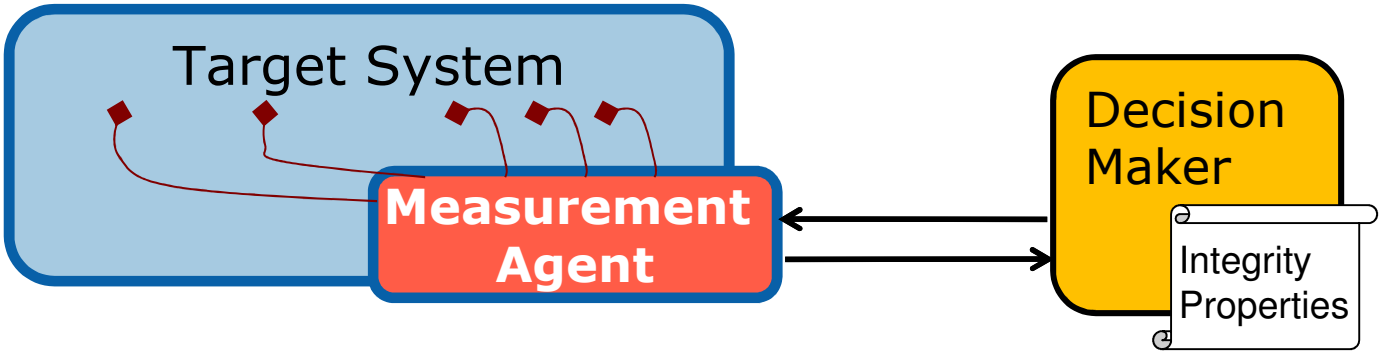
- Constant attacks exploiting vulnerabilities (e.g. buffer overflow, SQL injection)
- Configuration errors
- Malware (e.g., rootkits) are increasingly stealthy

One Solution: Integrity Checks through Remote Attestation

- Example malware: persistent control flow attacks



One Solution: Integrity Checks through Remote Attestation



- Integrity guarantee is only as strong as the completeness of the integrity model
- E.g., if integrity properties only cover system call table, a new rootkit can manipulate other function pointers (such as those found in device driver jump tables) to achieve its goal and remain undetected
- Question: Given the target software, how can we systematically and accurately identify its integrity properties?

Challenge of Runtime Attestation: Precise Integrity Models

- Two classic attestation errors when the model is not precise
  - False positives: the model is overly stringent
  - False negatives: the model is too loose
  - Both kinds of errors are undesirable

Integrity Model Derivation Approaches

- Manual analysis
  - Hard to scale, hard to counter novel attacks that move their targets to less-known places
- Dynamic analysis
  - Inability to explore all possible program execution paths
  - Gibraltar generates about 4,673 false positives
  - ReDAS has to create 70 training scenarios and 13,000 training sessions
- Static analysis …

Example Program

```
int v = 100;

while (1) {
    …
    if (tcp connect request from port 8088){
        v = v + 2;
    }
    …
}
```

- Dynamic analysis may report *v* as an invariant
- Static analysis will not

Our Contributions

- A program analysis tool that can automatically derive *global invariants* from source code, using static analysis
- A thorough study of global invariants detection for the Linux kernel
- An invariant monitor based on the result of the static analysis with low false positive and false negative rates

Outline

- Background
- Design and Implementation
- Evaluation
- Conclusion

Background

- Definition of Global Invariant
  - Global variable that has a *known-good* value during the runtime of the system
- Relevance in Integrity Protection
  - Represent the immutability of critical internal control data of the target system, e.g, Interrupt Descriptor Table (IDT),system call table, System Service Descriptor Table
  - Popular targets of attacks by rootkits (e.g., SucKIT, Hacker defender, NTIllusion, HE4Hook)
  - Basis for rootkit detectors (e.g., ReDAS, Copilot, and several commercial tools)

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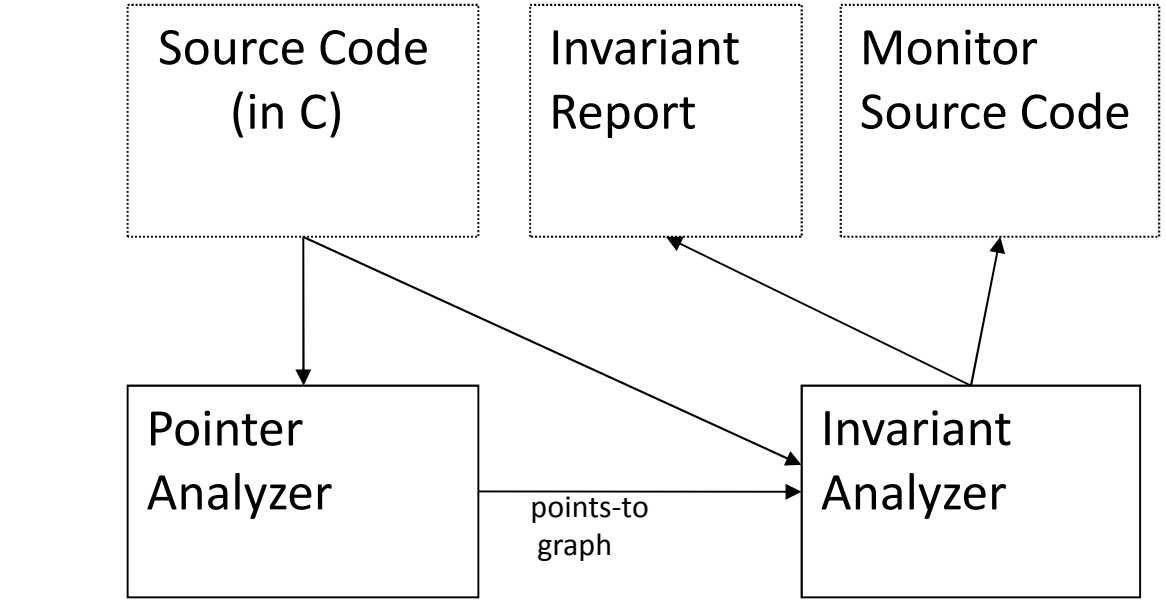
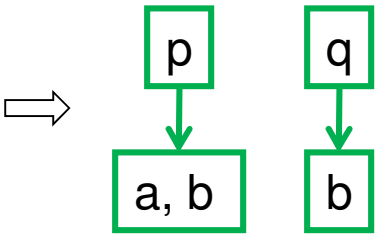
Design and Implementation (1)

- Architecture




```
int *p, *q, a, b;
p = &a; q = &b;
if (...) p = q;
*p = 2;
```



Design and Implementation (2)

- Goal: high precision by minimizing false negative and false positive rates
  - False negatives
    - Cause: a lack of fine-granularity and imprecise pointer analysis

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    - Example: field-insensitive analysis would consider the entire structure **v** as non-invariant, including **v.a**, and **v.c** → need to be field-sensitive

```
struct {char* a; int b; long c} v;
…
v.b = v.b + 2;
```

Design and Implementation (2)

- Goal: high precision by minimizing false negative and false positive rates
  - False negatives
    - Cause: a lack of fine-granularity and imprecise pointer analysis
    - Example: array-insensitive analysis would consider the entire array **v** as non-invariant, including **v[1]**, **v[2]**, …, **v[9]** → need to be array-sensitive

```
int v[10], m;
…
v[0] = v[0] + m;
```

Design and Implementation (2)

- Goal: high precision by minimizing false negative and false positive rates
  - False negatives
    - Cause: a lack of fine-granularity and imprecise pointer analysis
    - Example: conservative pointer analysis would consider **c** non-invariant as well → need precise pointer analysis

```
char* a; int b; int c;
int *p;
…
p = &b; …
*p = *p + 1;
```

Design and Implementation (2)

- Goal: high precision by minimizing false negative and false positive rates
  - False negatives
    - Cause: a lack of fine-granularity and imprecise pointer analysis
    - Solution: field- and array-sensitivity, precise pointer analysis
  - False positives
    - Causes: implicit assignments and incomplete points-to analysis

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    - Cause: a lack of fine-granularity and imprecise pointer analysis
    - Solution: field- and array-sensitivity, precise pointer analysis
  - False positives
    - Causes: implicit assignments and incomplete points-to analysis
    - Example: a structure-level assignment implicitly assigns to all fields. Here **foo = bar** modifies both **foo.a** and **foo.b**

```
struct {int a; int b;} foo, bar;
…
foo = bar;
```

Design and Implementation (2)

- Goal: high precision by minimizing false negative and false positive rates
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    - Cause: a lack of fine-granularity and imprecise pointer analysis
    - Solution: field- and array-sensitivity, precise pointer analysis
  - False positives
    - Causes: implicit assignments and incomplete points-to analysis
    - Example: If the points-to set of **q** does not contain **a**, then **a** is mistakenly considered an invariant → need precise pointer analysis

```
int a; int b; int *p, int *q;
p = &a; …;
if (some condition) {q = &b; …}
else {q = p; …}; …
*q = *q + 2;
```

Design and Implementation (2)

- Goal: high precision by minimizing false negative and false positive rates
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    - Cause: a lack of fine-granularity and imprecise pointer analysis
    - Solution: field- and array-sensitivity, precise pointer analysis
  - False positives
    - Causes: implicit assignments and incomplete points-to analysis
    - Solution: heuristics and precise pointer analysis

Design and Implementation (3)

- Assignment Recognition
  - Field Sensitivity: v.a and v.b are different variables
  - Array Sensitivity: v[0] and v[1] different variables
  - Pointer Analysis: use a precise algorithm called generalized one level flow (GOLF)
  - Union Support: treat each field of a union as an alias of other fields in the same union. E.g., **union uarg{int a; int b} c**, if **c.a** non-invariant, **c.b** non-invariant, either
  - Heuristics-base Assignment Recognition

Design and Implementation (3)

- Heuristics-base assignment recognition
  - Function prototype-based heuristic: capture implicit assignment by assembly code.
    - Example functions: memcpy, copy_from_user, spin_lock
  - Structure-level assignments
    - E.g., given **struct {int a; int b;} foo, bar** , **foo = bar** is translated into **foo.a = bar.a; foo.b = bar.b**

Design and Implementation (4)

- Invariant Recognition
  - Associate a flag (invariant or not) and a legal value list with each global variable
  - Scan global variable declarations and initialization functions and fill global variable's legal value list
  - Scan the remaining kernel functions. If a global variable, which is marked as an invariant, is assigned a non-constant value, or a constant value but the value is not in its legal value list, the analyzer marks it as a non-invariant
  - Generates a report about the invariant status of all global variables based on their flags

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Metrics and Methodology

- Target software: Linux kernel 2.4.32
- Metrics
  - False positives
  - False negatives
- Methodology
  - Comparing with a dynamic invariant detector
  - Checking invariants against real software (benign or malicious)

Test Cases

- Benign test cases

Test program	*Description*
ltp-2005	Linux Test Project: more than 700 test cases for the Linux kernel and more than 60 test cases for the network stack
Iperf	A network testing tool that measures the throughput of a network, thus exercising the network subsystem of the kernel
Andrew benchmark	A file system benchmark
Miscellaneous	Kernel compilation, ssh, scp, common commands

- Malicious test cases: real-world rootkits such as SuckIT

Comparing with a Dynamic Invariant Detector

Category	*Total #*	*# Error static*	*# Error dyna.*
S.NI, D.NI	154	0	0
S.NI, D.I	17,200	18(FN)	17,182(FP)
S.I, D.NI	0	0	0
S.I, D.I	136,778	1(FP)	1(FP)

S: Static, D: Dynamic; NI: Non-invariant; I: Invariant

Verification of the 17,200 Possible Non-invariants

- If a variable is directly modified: the assignment statement logged in the analysis report is straightforward evidence that the variable is a non-invariant

- If a variable is only indirectly modified through a pointer, our analyzer outputs the relevant statements from the source code that support the points-to relationship

Points-to Analysis Report Example

- Why ctrl_map[2] can be indirectly modified through the pointer key_map

<Name>ctrl_map[2]</Name>
<Invariant>No</Invariant>
<Reason1>
*(key_map + 0) = (unsigned short)(((2 << 8) | 126) ^ 61440);
vt.c:224, Indirectly modified through key_map.

Path from ctrl_map[2] to key_map:
<Label>ctrl_map[2]</Label>
<STMT>ctrl_map=&ctrl_map[2] defkeymap.c:65</STMT>
<Label>l_473154</Label>
<STMT>key_maps[4]=ctrl_map defkeymap.c:141</STMT>
<Label>l_479876</Label>
<STMT>key_map = key_maps[tmp.kb_table];vt.c:174
</STMT>

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Example Non-Invariants

Category	*Example variables*
List heads	acpi_bus_drivers.next arp_tbl.gc_timer.list.next
Locks	dev_base_lock.lock exec_domains_lock.lock
Auditing information	kernel_module.kallsyms_start kernel_module.kallsyms_end
Accounting information	console_sem.count.counter con_buf_sem.count.counter
Resource mgmt data	contig_page_data.node_zonelists[0].zones[0] contig_page_data.node_zones[0].free_area[0].map
Configuration data	FDC2,FLOPPY_DMA,FLOPPY_IRQ, can_use_virtual_dma,fifo_depth
Driver-specific data	eth0_dev.allmulti, eth0_dev.dev_addr[0]

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Experimental Evaluation of Accuracy

- We implement and run an Invariant Monitor based on the static analysis result
- False positive: only ONE false invariant out of 141,280
- False negative: successfully detect the SucKIT 2 rootkit, which modifies sys_call_table[59]

```
p=(struct timedia_struct*)0xc0272420;

if (((struct timedia_struct*)p)[3].num!=8)
 {printk(KERN_WARNING "Bad invariant
timedia_data[3].num \n");};
```

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Conclusion

- Core techniques
  - Static analysis – design and implement automated tools that can derive global invariants out of the target kernel without running it
  - Evaluate our methodology
    - Compare with dynamic analyer
  - Static analysis is a viable option for automated integrity property derivation and can have very low false positive and false negative rates