CE 874 - Secure Software Systems

Taint Analysis

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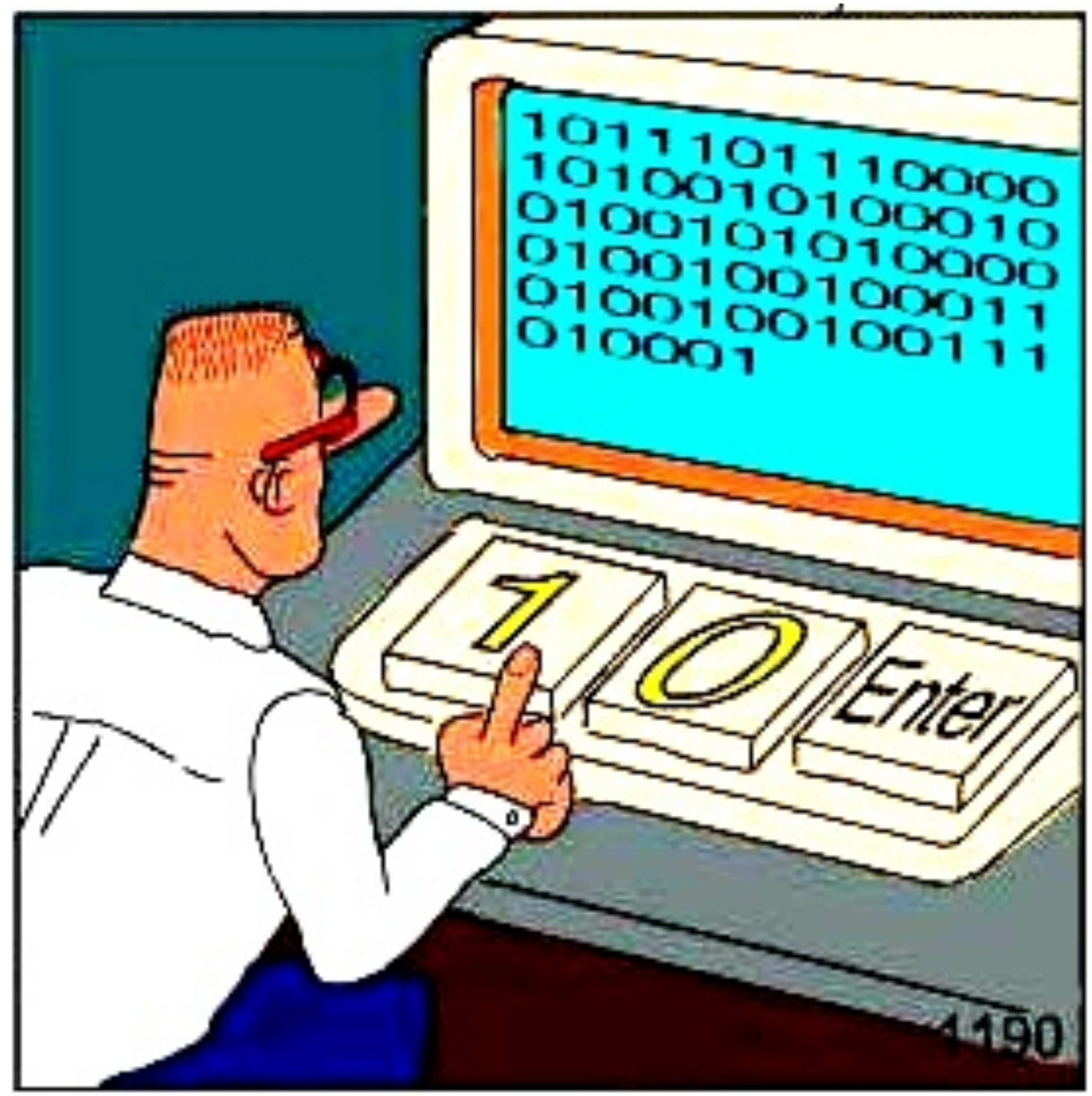
Acknowledgments: Some of the slides are fully or partially obtained from other sources. Reference is noted on the bottom of each slide, when the content is fully obtained from another source. Otherwise a full list of references is provided on the last slide.

Run-Time protection/enforcement

- In many instances we only have access to the binary
- How do we analyze the binary for vulnerabilities?
- How do we protect the binary from exploitation?
- This would be our topic for the next few lectures



REAL Programmers code in BINARY.

Why Binary Code?

- Access to the source code often is not possible:
  - Proprietary software packages
  - Stripped executables
  - Proprietary libraries: communication (MPI, PVM), linear algebra (NGA), database query (SQL libraries)
- Binary code is the only authoritative version of the program
  - Changes occurring in the compile, optimize and link steps can create non-trivial semantic differences from the source and binary
- Worms and viruses are rarely provided with source code

Binary Analysis and Editing

- **Analysis**: processing of the binary code to extract syntactic and symbolic information
  - Symbol tables (if present)
  - Decode (disassemble) instructions
  - Control-flow information: basic blocks, loops, functions
  - Data-flow information: from basic register information to highly sophisticated (and expensive) analyses

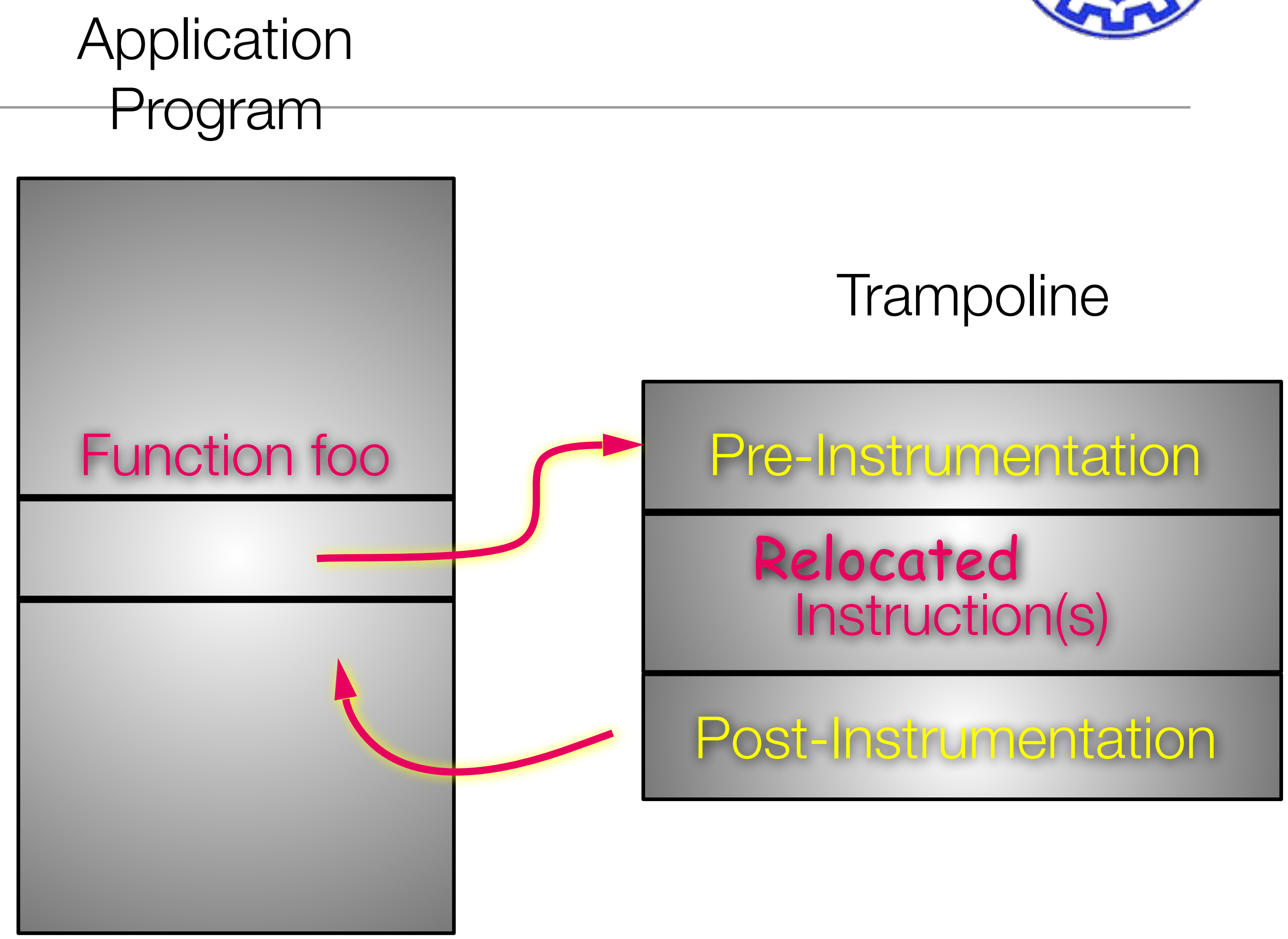
Binary Analysis and Editing

- **Binary rewriting**: static (before execution) modification of a binary program
  - Analyze the program and then insert, remove, or change the binary code, producing a new binary
- **Dynamic instrumentation**: dynamic (during execution) modification of a binary program
  - Analyze the code of the running program and then insert, remove, or change the binary code, changing the execution of the program
  - Can operate on running programs and servers

Uses of Binary Analysis and Editing

- Cyber-forensics
  - Analysis: understand the nature of malicious code
  - Binary-rewriting: produce a new version of the code that might be instrumented, sandboxed, or modified for study
  - Dynamic instrumentation: same features, but can do it interactively on an executing program
  - Hybrid static/dynamic: control execution and produce intermediate versions of the binary that can be re-executed (and further instrumented)
- Program tracing: instructions, memory accesses, function calls, system calls, . . .
- Debugging
- Testing, Performance profiling Performance modeling
- Reverse engineering

Binary patch



pop ecx; puts the return address to ecx
jmp ecx; jumps to the return address

After Patch:

pop ecx; puts the return address to ecx
cmp ecx , 0x08048456 ; check that we return to the right place
jne 0x41414141 ; crash
jmp ecx; effectively return

Dynamic Binary Instrumentation

- A DBI is a way to execute an external code before or/and after each instruction/routine

```
initial_instruction_1
initial_instruction_2
initial_instruction_3
initial_instruction_4
```

```
jmp_call_back_before
initial_instruction_1
jmp_call_back_after

jmp_call_back_before
initial_instruction_2
jmp_call_back_after

jmp_call_back_before
initial_instruction_3
jmp_call_back_after

jmp_call_back_before
initial_instruction_4
jmp_call_back_after
```

- With a DBI you can:
  - Analyze the binary execution step-by-step
    - Context memory
    - Context registers
  - Only analyze the executed code

Available Tools

- Binary re-writing:
  - e.g.: Alto, Vulcan, Diablo, etc.
- Binary Instrumnetation:
  - e.g. PIN, Valgrind, DynInst, etc

Dynamic Taint Analysis for Automatic Detection, Analysis, and Signature Generation of Exploits on Commodity Software, J. Newsome and D. Song, NDSS 2005.

Motivation

- Worms exploit several software vulnerabilities
  - buffer overflow
  - “format string” vulnerability
- Attack detectors ideally should:
  - Detect new attacks and detect them early
  - Be easy to deploy
  - Few false positives and false negatives
  - Be able to automatically generate filters and sharable fingerprints

Motivation (contd.)

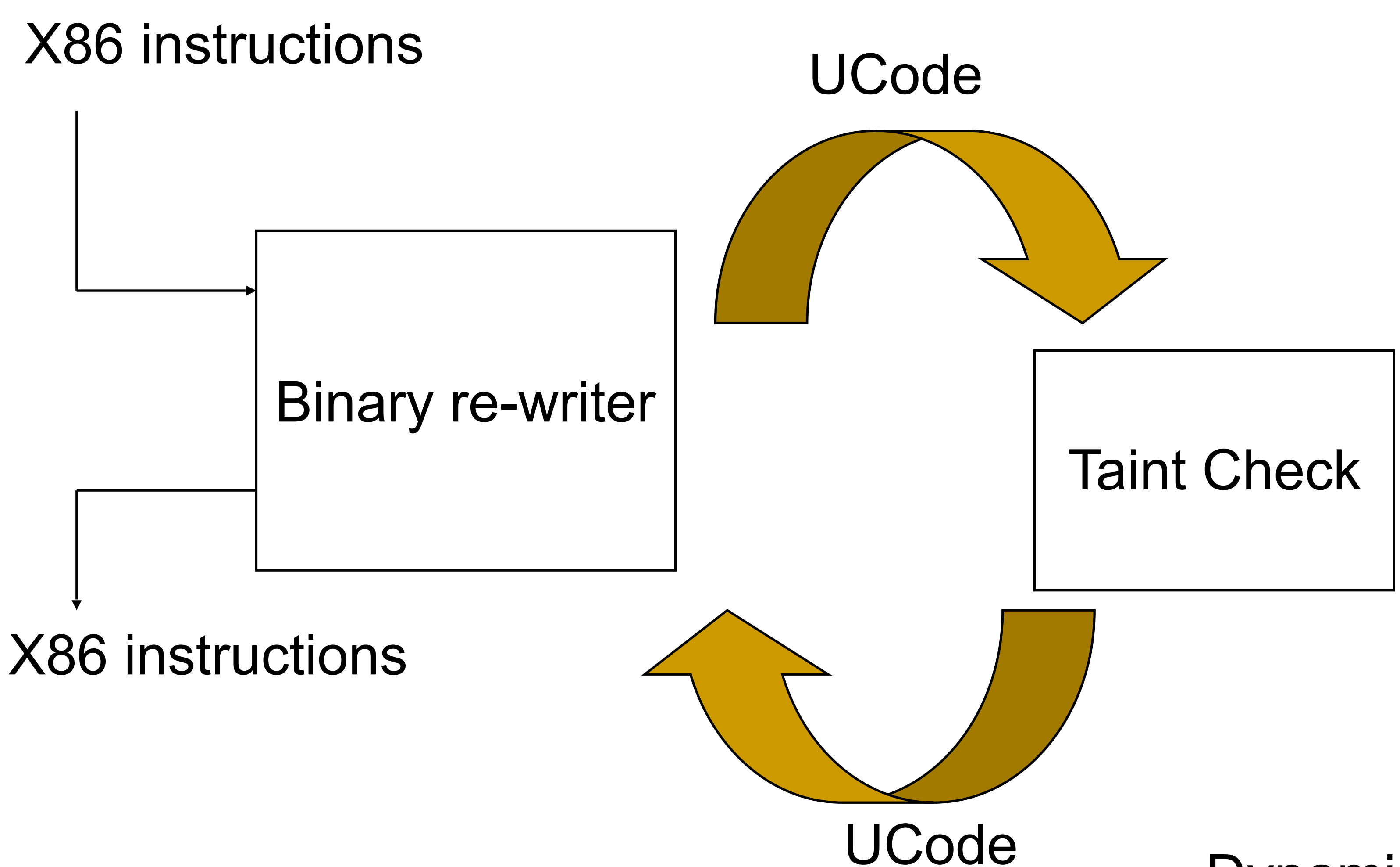
- Attack detectors are:
  - Coarse grained detectors
    - Detect anomalous behavior but do not provide detailed information about the vulnerability
    - Scan detectors, anomaly detectors
  - Fine grained detectors are highly desirable
    - Detect attacks on programs vulnerabilities and hence provide detailed information about the attack
    - But some require source code (typically not available for commercial software), recompilation, bounds checking, library recompilation, source code modification, etc.
  - Other options: content-based filtering (e.g., IDS' such as snort and Bro), but automatic signature generation is hard

TaintCheck: Basic Ideas

- Program execution normally derived from trusted sources, not attacker input
- Mark all input data to the computer as “tainted” (e.g., network, stdin, etc.)
- Monitor program execution and track how tainted data propagates (follow bytes, arithmetic operations, jump addresses, etc.)
- Detect when tainted data is used in dangerous ways

Step 1: Add Taint Checking code

- TaintCheck first runs the code through an emulation environment (Valgrind) and adds instructions to monitor tainted memory.



Dynamic taint analysis

TaintCheck Detection Modules

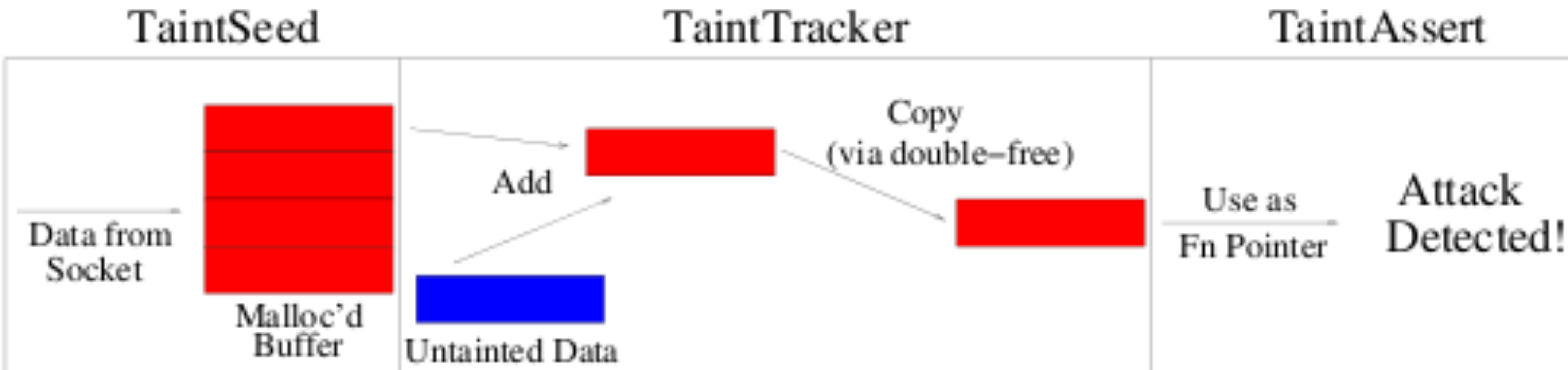


Figure 1. TaintCheck detection of an attack. (Exploit Analyzer not shown).

- TaintSeed: Mark untrusted data as tainted
- TaintTracker: Track each instruction, determine if result is tainted
- TaintAssert: Check is tainted data is used dangerously
  - Jump addresses: function pointers or offsets
  - Format strings: is tainted data used as a format string arg?
  - System call arguments
  - Application or library customized checks

TaintSeed

- Marks any data from untrusted sources as “tainted”
  - Each byte of memory has a four-byte shadow memory (ick!) that stores a pointer to a Taint data structure if that location is tainted
    - records the system call number, a snapshot of the current stack and a copy of the data that was written.
  - Else store a NULL pointer

Memory is mapped to TDS

TaintTracker

- Tracks each instruction that manipulates data in order to determine whether the result is tainted.
  - When the result of an instruction is tainted by one of the operands, TaintTracker sets the shadow memory of the result to point to the same Taint data structure as the tainted operand.

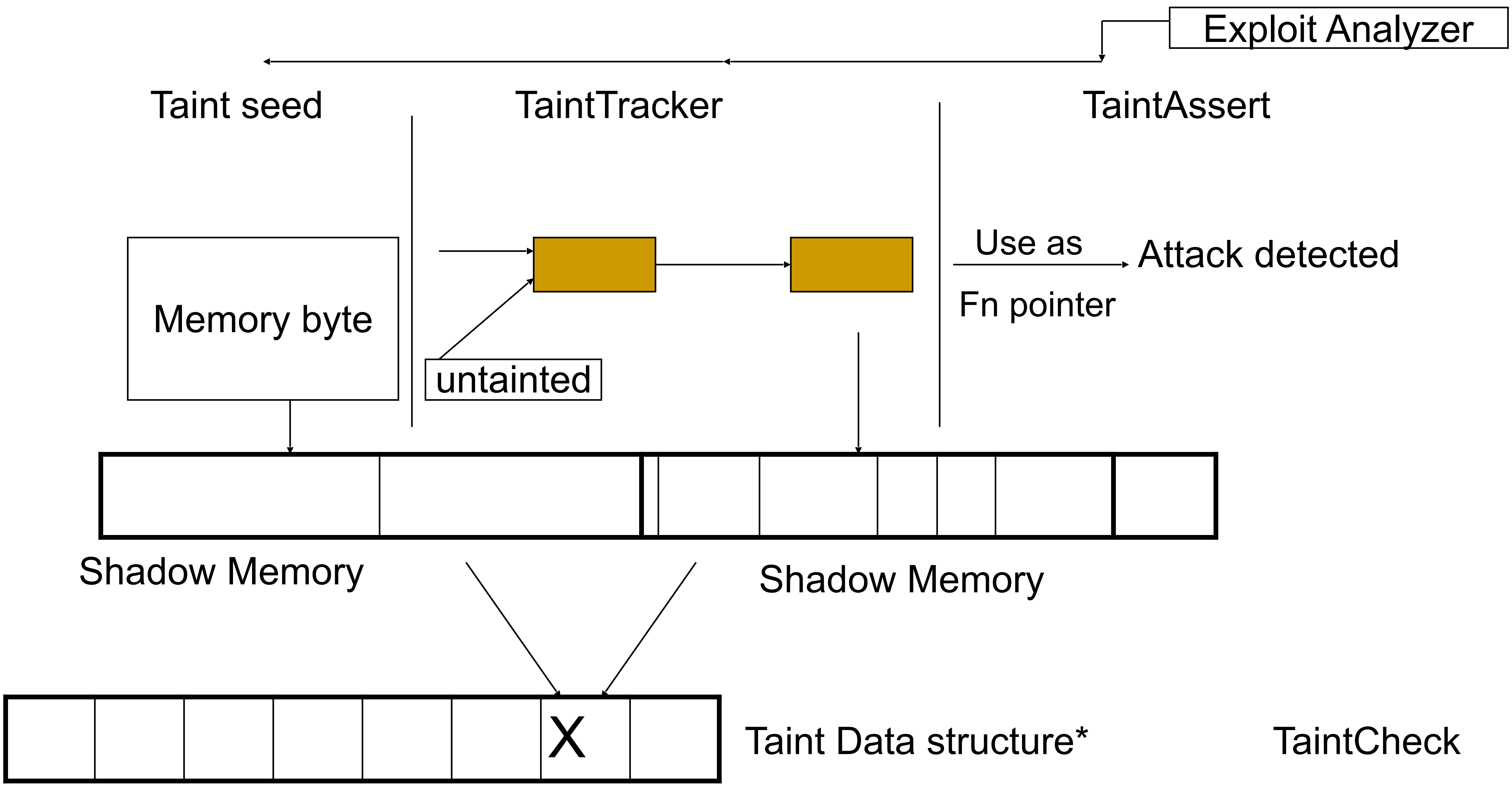
Memory is mapped to TDS

Result is mapped to TDS

TaintAssert

- Checks whether tainted data is used in ways that its policy defines as illegitimate

TaintCheck Operation



*TDS holds the system call number, a snapshot of the current stack, and a copy of the data that was written

Exploit Analyzer

- Provides useful information about how the exploit happened, and what the exploit attempts to do
- Useful to generate exploit fingerprints

- Usage:
  - Identifying vulnerabilities.
  - Generating exploit signature.

Memory is mapped to TDS — Operand is mapped to TDS ← vulnerability

Dynamic Taint Analysis

- Jump addresses:
  - Checks whether tainted data is used as a jump target
  - Instrument before each Ucode jump instruction
- Format strings:
  - Checks whether tainted data is used as format string argument
  - Intercept calls to the printf family of functions
- System call arguments:
  - Checks whether the arguments specified in system calls are tainted
  - Optional policy for execv system call
- Application or library-specific checks:
  - To detect application or library specific attacks

When does TaintCheck Fail?

- A false negative occurs if an attacker can cause sensitive data to take on a value without that data becoming tainted
  - E.g. if (x == 0)y = 0; else if (x == 1) y = 1; ...
- If values are copied from hard-coded literals, rather than arithmetically derived from the input
  - IIS translates ASCII input into Unicode via a table
- If TaintCheck is configured to trust inputs that should not be trusted
  - data from the network could be first written to a file on disk, and then read back into memory

When does TaintCheck give a False Positive?

- TaintCheck detects that tainted data is being used in an illegitimate way even when there is no attack taking place. Possibilities:
  - There are vulnerabilities in the program and need to be fixed, or
  - The program performs sanity checks before using the data

tainted untainted

Δ

Var	Val

➡ ● = get_input()
y = x + 42
...
goto y

Input is tainted

TaintSeed

τ

Var	Tainted?

tainted untainted

= get_input()

= +

…

goto y

Data derived from user input is tainted

TaintTracker

Δ

Var	Val
x	7
y	49

τ

Var	Tainted?
x	T
y	T

tainted untainted

= get_input()

= +

...

goto

Policy Violation Detected

TaintAssert

Δ

Var	Val
x	7
y	49

τ

Var	Tainted?
x	T
y	T

x = get_input()

y = …

…

goto y

Jumping to overwritten return address

…
strcpy(buffer,argv[1]);
…
return ;

Memory Load

Variables

Δ

Var	Val
x	7

τ

Var	Tainted?
x	T

Memory

μ

Addr	Val
7	42

τ_μ

Addr	Tainted?
7	F

Problem: Memory Addresses

```
   = get_input(            )
y  = load(   )
...
goto  y
```

All values derived from user input are tainted??

Δ

Var	Val
x	7

μ

Addr	Val
7	42

τ_μ

Addr	Tainted?
7	F

Policy 1: Taint depends only on the memory cell

= get_i

= load(

...

goto

Undertainting

Failing to identify tainted values
- e.g., missing exploits

Taint Propagation

Var	Val
	7

ldr	Val
7	42

τ_μ

Addr	Tainted?
7	F

Policy 2: If either the address or the memory cell is tainted, then the value is tainted

= get_i
= load
...
goto

Memory
Address expression is tainted
printa
printb

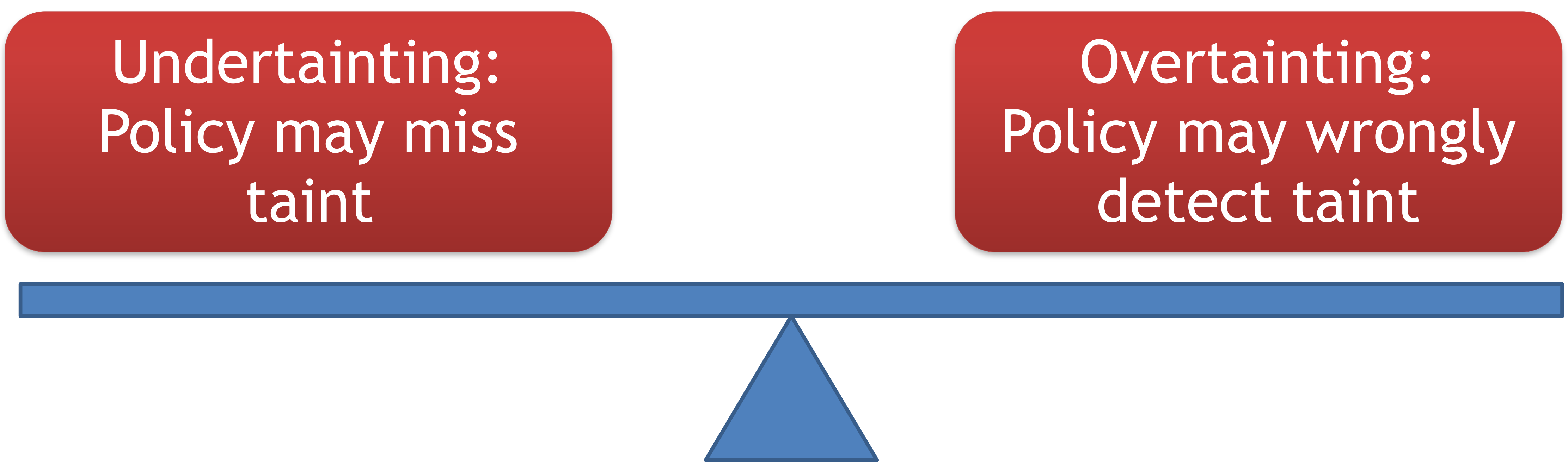
Taint Propagation

Overtainting

Unaffected values are tainted
- e.g., exploits on safe inputs

General Challenge

- State-of-the-Art is not perfect for all programs



Compatibility with Existing Code

- Does TaintCheck raise false alerts?
- Networked programs: 158K+ DNS queries
  - No false +ves
- All (!!) client and non-network programs (tainted data is stdin):
  - Only vim and firebird caused false +ves (data from config files used as offset to jump address)

Attack Detection: Synthetic + Actual Exploits

Program	Overwrite Method	Overwrite Target	Detected
ATPhttpd	buffer overflow	return address	✔
synthetic	buffer overflow	function pointer	✔
synthetic	buffer overflow	format string	✔
synthetic	format string	none (info leak)	✔
cfingerd	`syslog` format string	GOT entry	✔
wu-ftpd	`vsnprintf` format string	return address	✔

Evaluation - Evaluation of attack detection

- Synthetic exploits
  - They wrote small programs for:

Return Address	Function Pointer	Format String
“gets” for long input	Same	Line input from user
Overwrote the stack – overwrote return address	Overwrote the stack – overwrote function pointer	Overwrote format string
Attack detected as return addr was tainted from user input	Attack detected as func pointer was tainted from user input	TaintCheck determined correctly when the format string was tainted

Evaluation - Evaluation of attack detection

- Actual exploits: TaintCheck evaluated on exploits to three vulnerable servers: a web server, a finger daemon, and an FTP server.

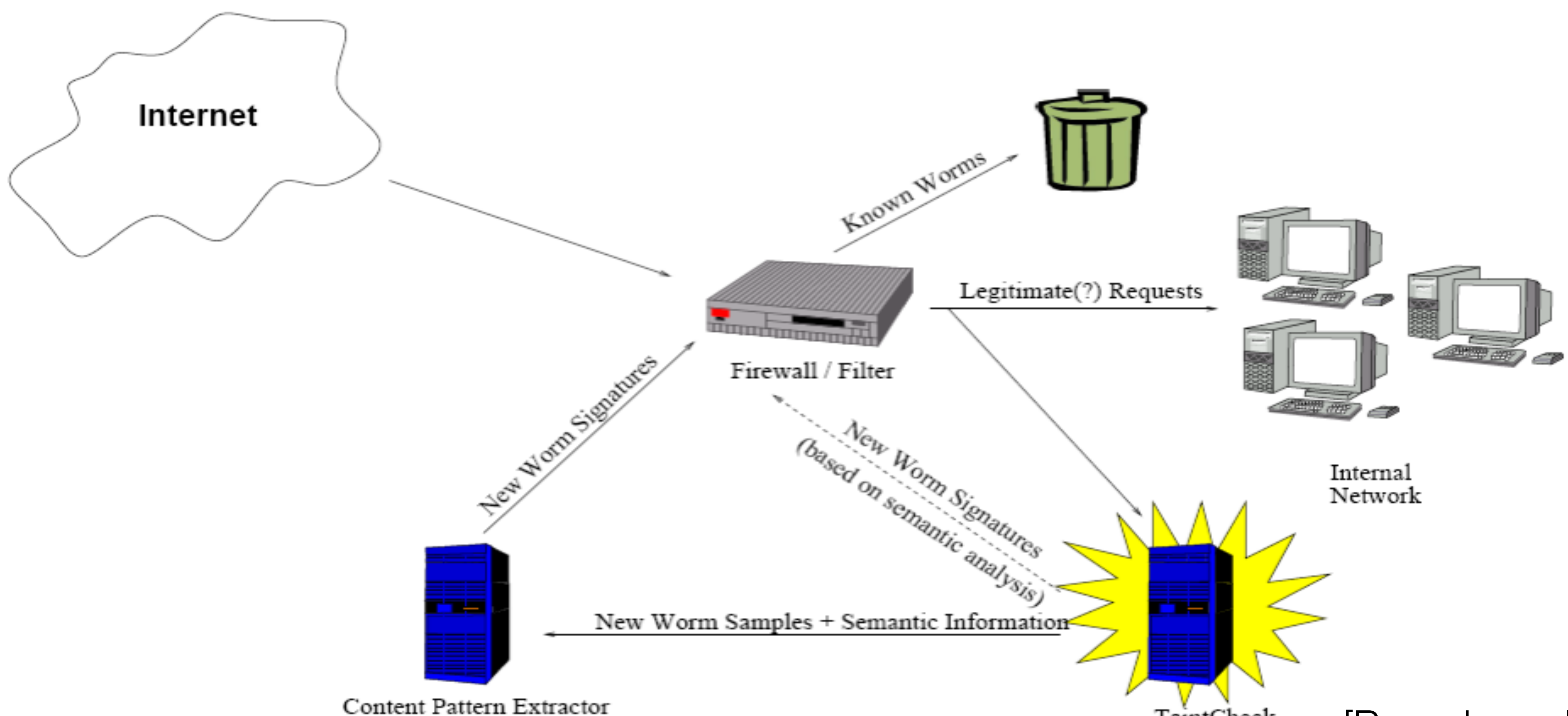
ATPhttpd exploit	cfingerd exploit	wu-ftpd exploit
Web server program	Finger daemon	ftp
Ver 0.4b and lower are vulnerable to buffer overflow	Ver 1.4.2 and lower are vulnerable to format string	Version 2.6.0 of wu-ftpd has a format string vulnerability in a call to vsnprintf.
malicious GET request with a very long file name (shellcode and a return address) was sent to server. Return address overwritten so when func retruns it jumps to shell code inside the file name ? remote shell for attacker	When prompts for a user name, exploit responds with a string beginning with “version” + malicious code - cfingerd copies the whole string into memory, but only reads to the end of the string “version”. Malicious code in memory starts working	Format string to overwrite the return address was detected
TaintCheck detected return addr was tainted and identified the new value	Detected also	TaintCheck successfully detects both that the format string supplied to vsnprintf is tainted, and that the overwritten return address is tainted.

Performance Evaluation – CPU Bound Process

- Hardware: 2.00 GHz Pentium 4, 512 MB RAM, RedHat 8.0
- Application: bzip2(15mb)
  - Normal runtime 8.2s
  - Valgrind nullgrind skin runtime: 25.6s (3.1x)
  - Memcheck runtime: 109s (13.3x)
  - TaintCheck runtime: 305s (37.2x)

Automatic Signature Generation

- Automatic semantic analysis based signature generation
  - Find value used to override return address – typically fixed value in the exploit code
  - Sometimes as little as 3 bytes! See paper for details



[Papadopoulos’11]

Other Applications

- ?

Acknowledgments/References (1/2)

- [B. P. Miller'06] A Framework for Binary Code Analysis, and Static and Dynamic Patching, Barton P. Miller, Jeffrey Hollingsworth, February 2006.
- [Papadopoulos'11] CS451, Christos Papadopoulos, CSU, Spring 2011. Original slides by Devendra Salvi (2007). Based on "Dynamic Taint Analysis for Automatic Detection, Analysis, and Signature Generation of Exploits on Commodity Software", J. Newsome and D. Song, NDSS 2005.
- [EECS 583'12] – Class 21 Research Topic 3: Dynamic Taint Analysis, University of Michigan December 5, 2012. Based on "All You Ever Wanted to Know about Dynamic Taint Analysis and Forward Symbolic Execution (but Might Have Been Afraid to Ask)", E. J. Schwartz, T. Avgerinos, D. Brumley, IEEE S&P, 2010.
- [Brumley'10] All You Ever Wanted to Know about Dynamic Taint Analysis and Forward Symbolic Execution (but Might Have Been Afraid to Ask), E. J. Schwartz, T. Avgerinos, D. Brumley, IEEE S&P, 2010.

Acknowledgments/References (2/2)

- [CS-6V81] System Security and Malicious Code Analysis, S. Qumruzzaman, K. Al-Naami, Spring 2012. Based on “Dynamic Taint Analysis for Automatic Detection, Analysis, and Signature Generation of Exploits on Commodity Software”, J. Newsome and D. Song, NDSS 2005.
- [Salwan’15] Dynamic Binary Analysis and Instrumentation Covering a function using a DSE approach, J. Salwan, Security Day, January 2015.