Automatic Discovery of API-Level Exploits

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Two definitions

Vulnerability

An error in a software package that allows for unintended behavior.

Exploit

A sequence of operations that attacks the vulnerability, typically with malicious intent.

Motivation

```
//Format & enter into LOG
void log(char *fmt,...){
  fprintf(LOG,fmt,...);
  return;
}

//Call log on user input
int foo(void){
  char buf[LEN];
  …
  fgets(buf,LEN-1,FILE);
  log(buf);
  …
}
```

- Format-string vulnerability
  - `buf = “%s%s%s”`
  - `fprintf(LOG,“%s%s%s”)`

- Insufficient arguments to `fprintf.`Possible outcomes
  - Unintelligible log entry.
  - Program crash.
  - Hacker takes over program!

Motivation

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  …
}
```

- Tools to find format-string vulnerabilities: Percent-S [Shankar et al. USENIX Security 2001]
  - Finds user-controlled format-strings (using type-qualifiers)
- But, tools to *systematically* find *exploits* against such vulnerabilities?
- Trend is similar for other kinds of vulnerabilities.

Motivation

Many vulnerability-detection tools. Few, if any, exploit-finding tools.

Q: What is different about exploit-finding?

Q: Is exploit finding worth the effort?

Q: Isn’t finding exploits a black-hat activity?

Motivation

Many vulnerability-detection tools. Few, if any, exploit-finding tools.

Q: What is different about exploit-finding?

A: Modeling low-level implementation details.

Q: Is exploit finding worth the effort?

A: Yes!

Q: Isn’t finding exploits a black-hat activity?

A: Not necessarily!

Exploit-finding can benefit, and improve the quality of, vulnerability-detection tools.

Overview of results

- We study exploit-finding by considering a class of exploits called *API-Level Exploits.*

- We present a framework to:
  - Model low-level details of an API’s implementation.
  - Automatically analyze the model and find exploits.

- Two real-world instantiations:
  - **`printf`**-family format-string exploits.
  - IBM Common Cryptographic Architecture (CCA) API.

Talk structure

- Motivation and Overview.
- Framework for finding API-level exploits.
- Example: format-string exploit-detector.
  - Overview of **`printf`** and format-string exploits.
  - Instantiating **`printf`** in our framework.
  - Results.
  - Comparison with other tools.
- Related work.
- Conclusions.

API-Level Exploits

- What are API-Level exploits?
  - A sequence of API operations *allowed* by the underlying system.
  - But, compromises the security of the system.

- Example: [Chen and Wagner, CCS 2002]
  - System: UNIX, API: system calls.
  - **`setuid(0)`** followed by **`execl`** can lead to **`root`** privileges.

Framework for modeling APIs

- Find exploits:
  - Model low-level details of the system.
- Only check allowed sequences:
  - Otherwise, false alarms.
  - Must encode sets of allowed sequences.
  - Example: OS, system calls. Want to check if a particular application can compromise the OS.
  - Only check sequences of system calls generated by that application [Giffin et al. NDSS 2004]

Framework for modeling APIs

- Find exploits:
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- Model system S as:

$$\boxed{S = (V, \mathrm{Init}, \Sigma, L)}$$

Framework for modeling APIs

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- Model system S as:

$$\boxed{S = (V, \text{Init}, \Sigma, L)}$$

Finite set of variables, denoting current state of S.
Possibly with values from an infinite domain

Framework for modeling APIs

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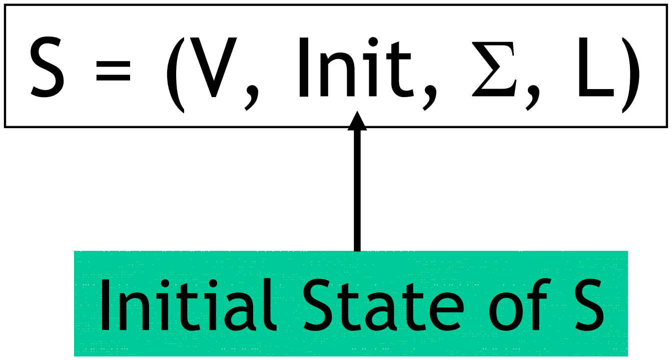

$$\boxed{S = (V, \mathit{Init}, \Sigma, L)}$$

Initial State of S

Framework for modeling APIs

- Find exploits:
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- Only check allowed sequences:
  - Otherwise, false alarms.
  - Must encode sets of allowed sequences.
- Model system S as:

$$\boxed{S = (V, \text{Init}, \Sigma, L)}$$

Finite set of API operations. Semantics of each operation specified using Pre- and Post-contitions

Framework for modeling APIs

- Find exploits:
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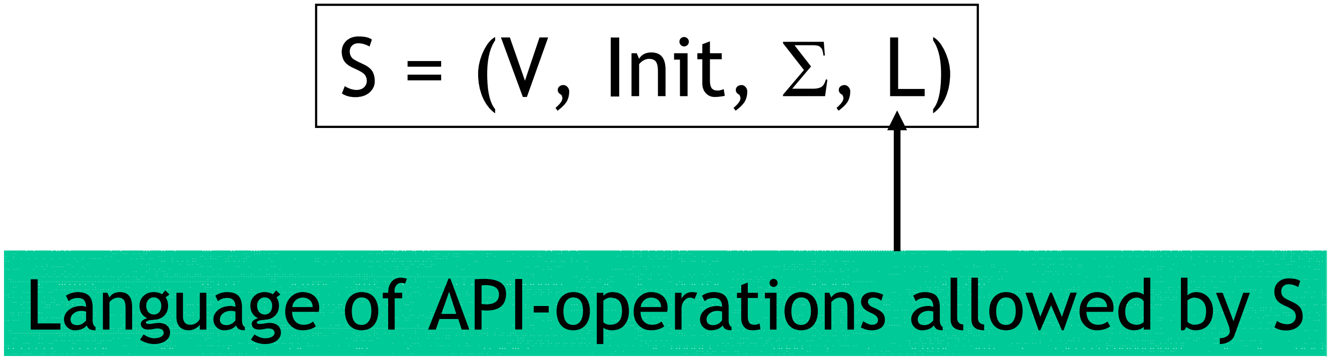

$$S = (V, \mathrm{Init}, \Sigma, L)$$

Language of API-operations allowed by S

Finding API-Level Exploits

- Specify what is Bad for the system S.
- Reduce to satisfiability.
- Is there a sequence of k operations, such that
  - For any finite value of k,
  - S initially satisfies predicate Init,
  - The sequence of operations is in L,
  - The state of S after the k^{th} operation satisfies Bad

Finding API-Level Exploits

- Specify what is Bad for the system S.
- Reduce to satisfiability.
- Is there a sequence of k operations, such that
  - For any finite value of k,
  - S initially satisfies predicate Init,
  - The sequence of operations is in L,
  - The state of S after the kth operation satisfies Bad
- Not surprisingly, undecidable.
  - k is unbounded.
  - In general, system is infinite-state.

Finding API-Level Exploits

- Our approach:
  - Bound k, the length of the sequence of API operations.
  - Model check.
- In effect, checking all allowed sequences of length k for exploits.

Talk structure

- Motivation and Overview.
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Format-string vulnerabilities

- Allow intruder to assume privileges of the victim program.
- Highly prevalent. [http://www.securiteam.com/exploits]
- Vulnerability-detection tools available.
  - Example: Percent-S.
- Goals of our tool:
  - Systematically find exploits against such vulnerabilities.
  - Work with real-world applications.

Overview of **`printf`**

```
//Format & enter into LOG
void log(char *fmt,...){
  fprintf(LOG,fmt,...);
  return;
}

//Call log on user input
int foo(void){
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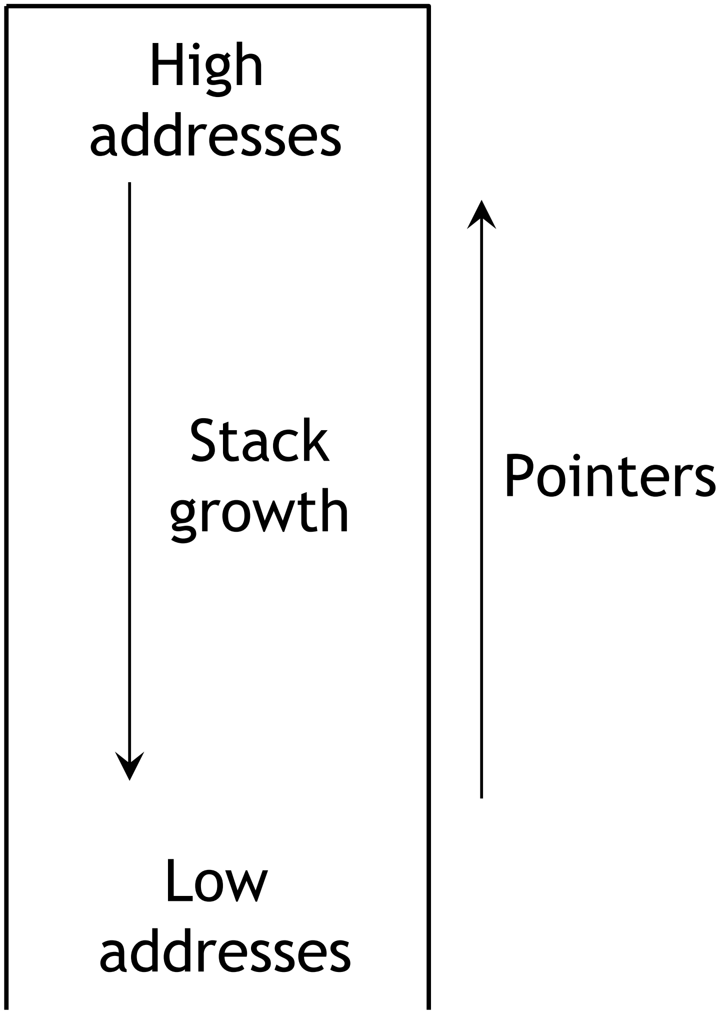
  …
  fgets(buf,LEN-1,FILE);
  log(buf);
  …
}
```



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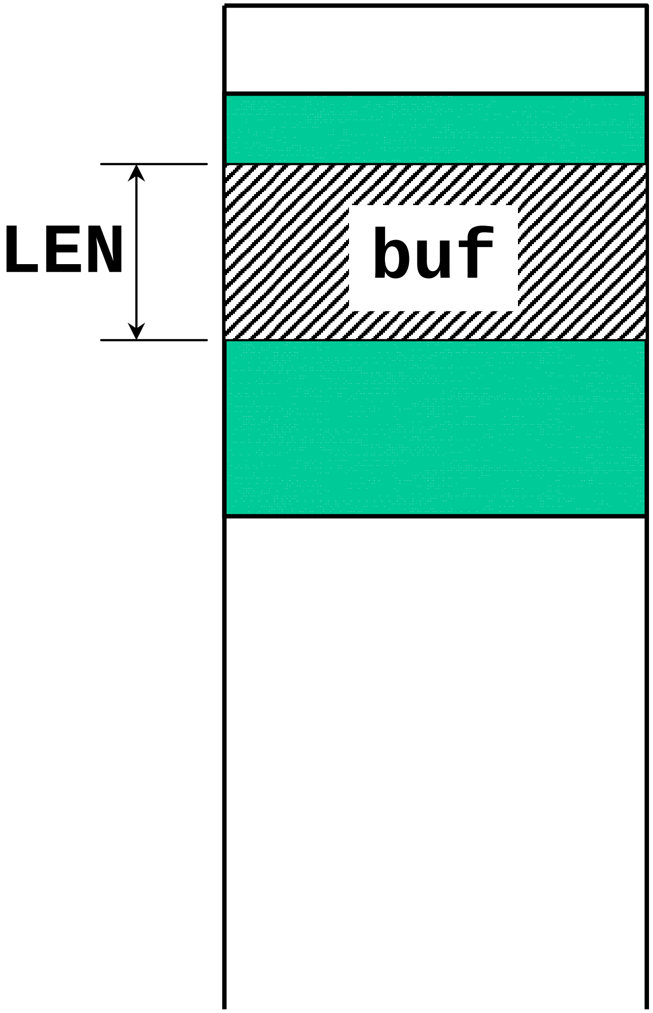

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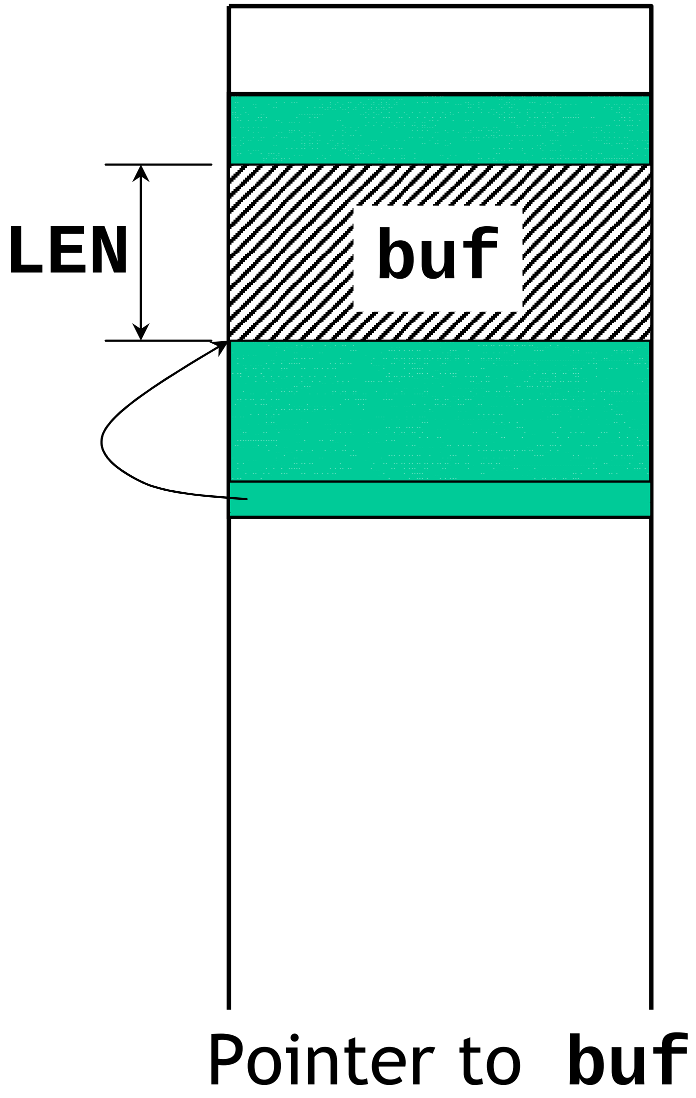

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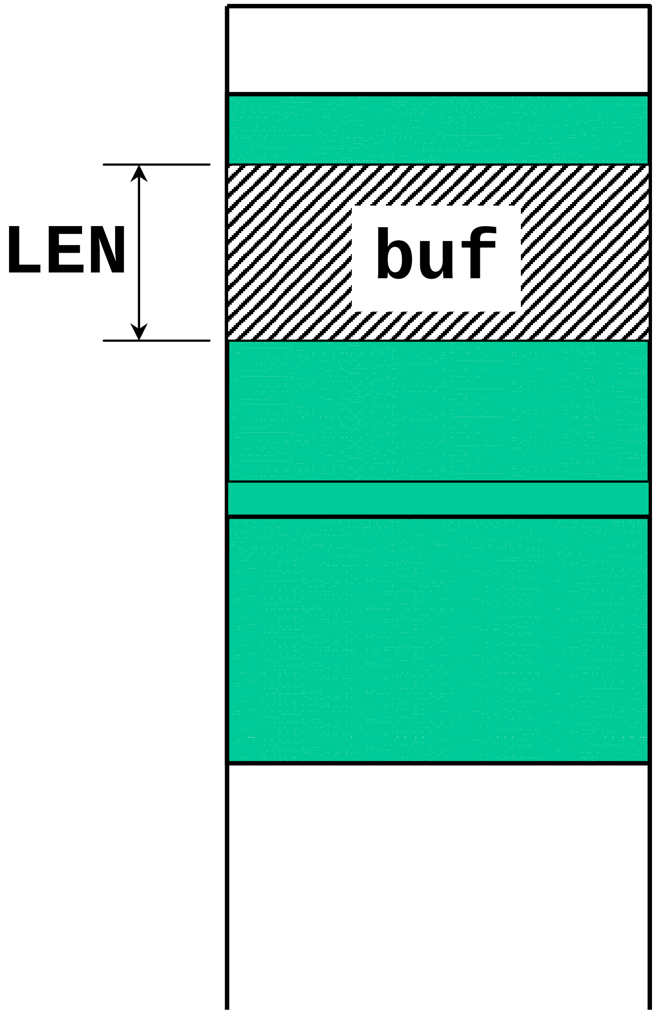

Stack frame of `log`

Overview of **printf**

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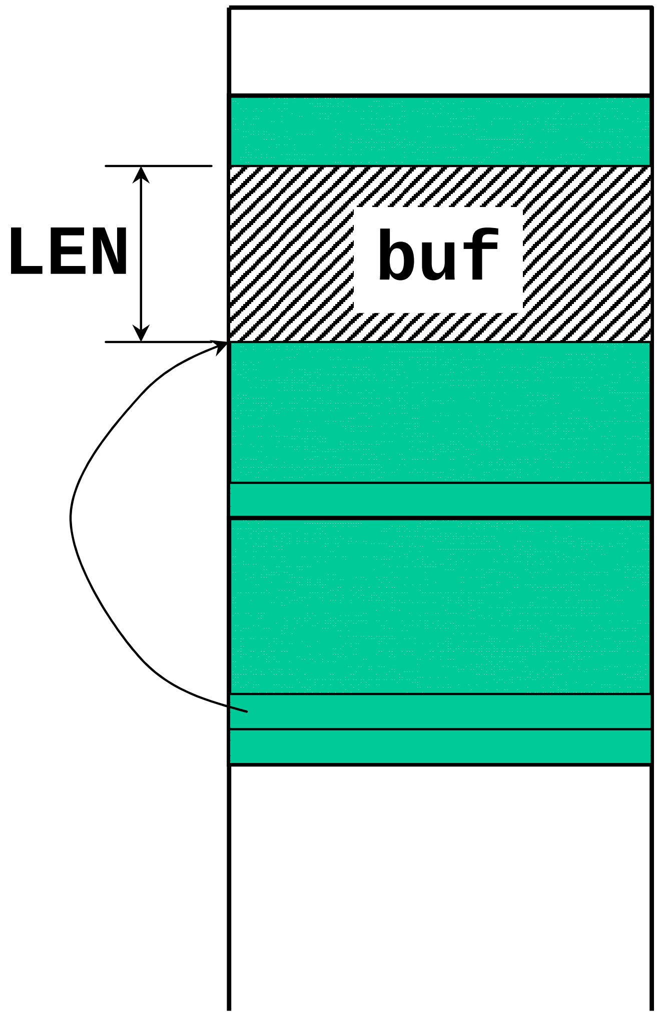

Pointer to **buf**

Overview of **printf**

```
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void log(char *fmt,...){
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   return;
}

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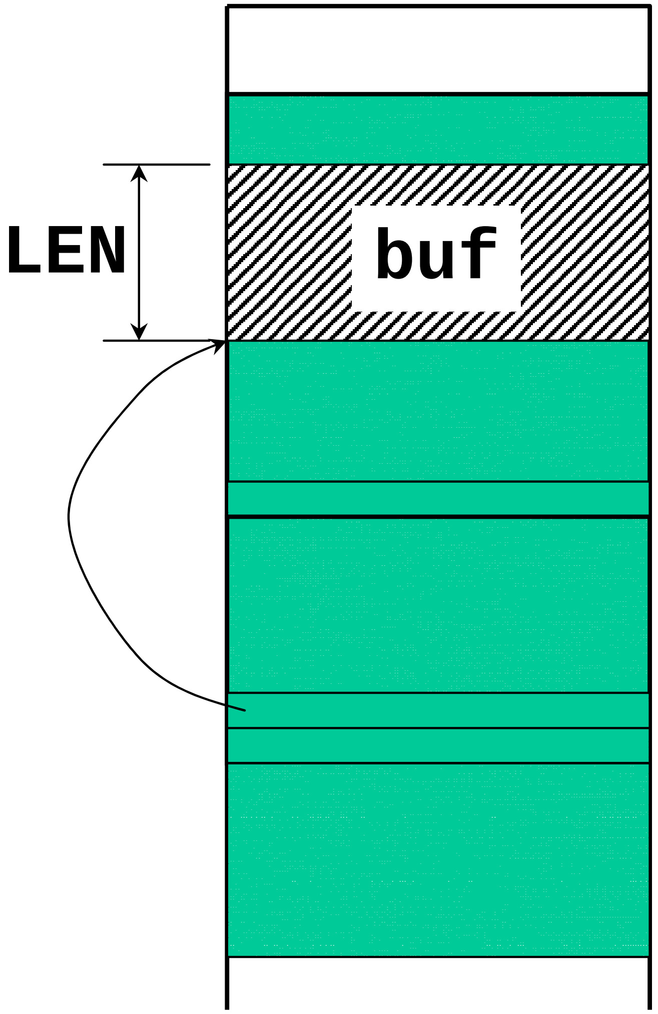
   …
}
```



Stack frame of **fprintf**

Overview of **`printf`**

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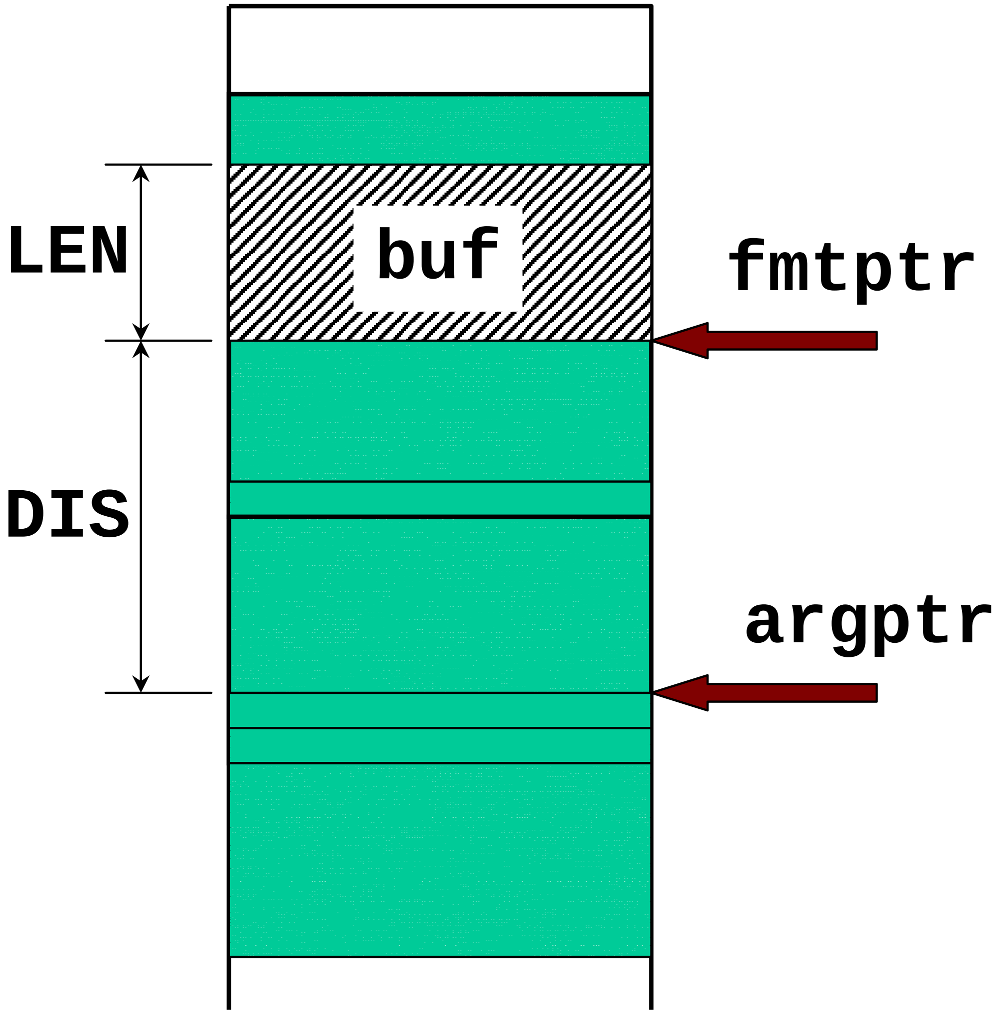

Overview of **`printf`**

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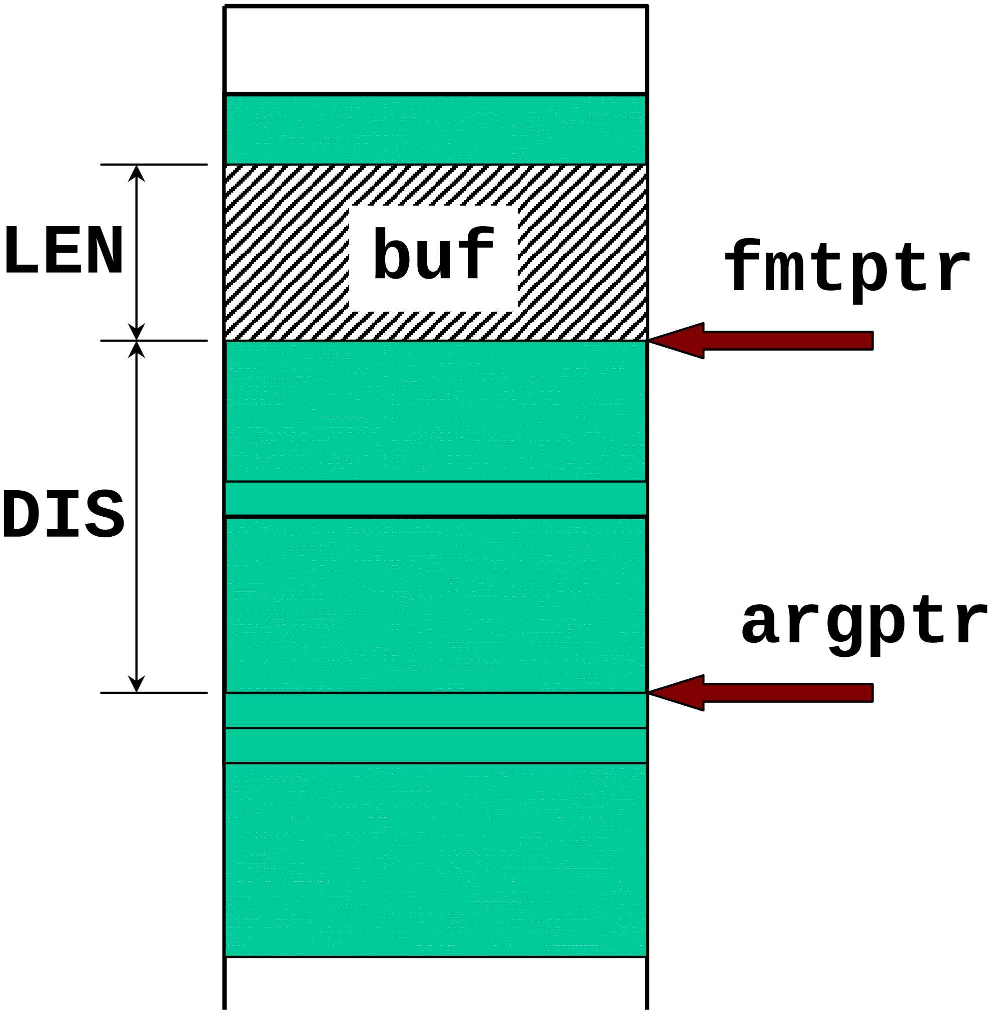

buf = “%x%x%s”

Overview of **printf**

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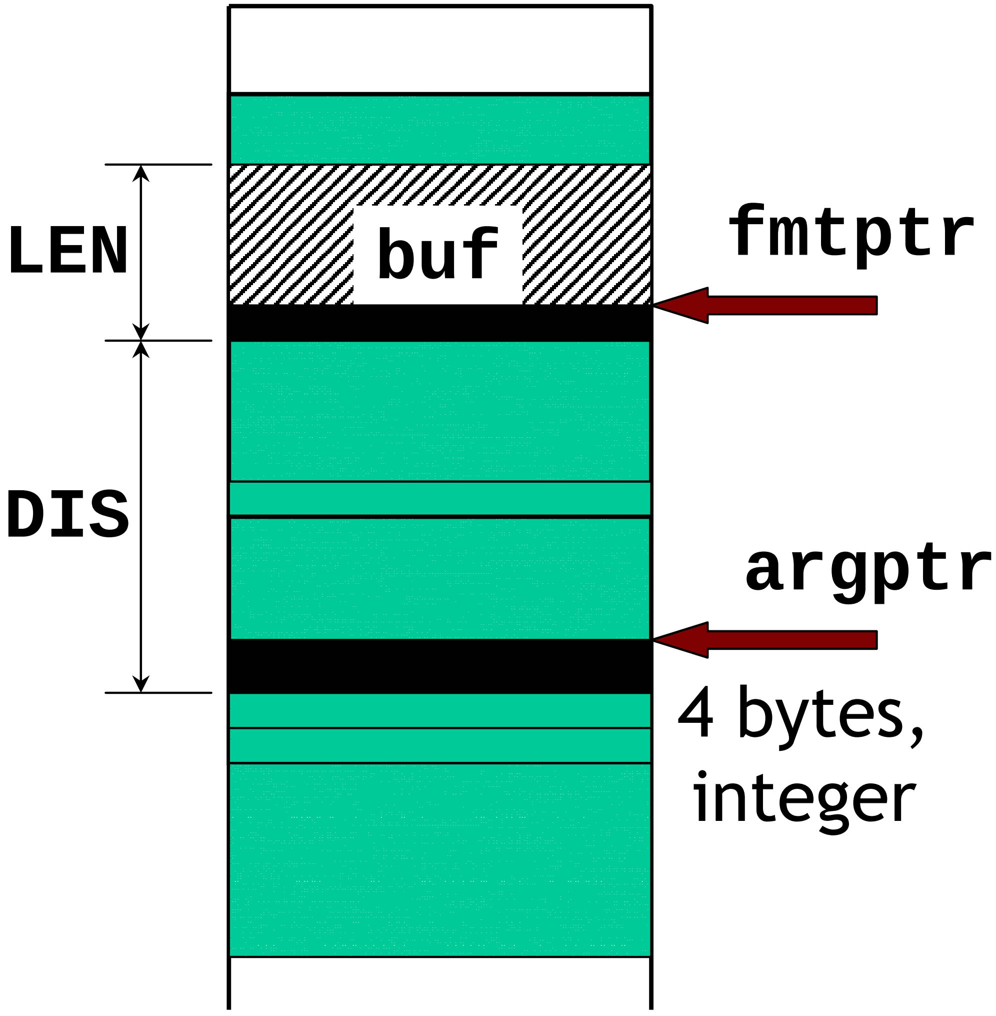

buf = “🟥%x%s”

Overview of printf

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//Format & enter into LOG
void log(char *fmt,...){
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//Call log on user input
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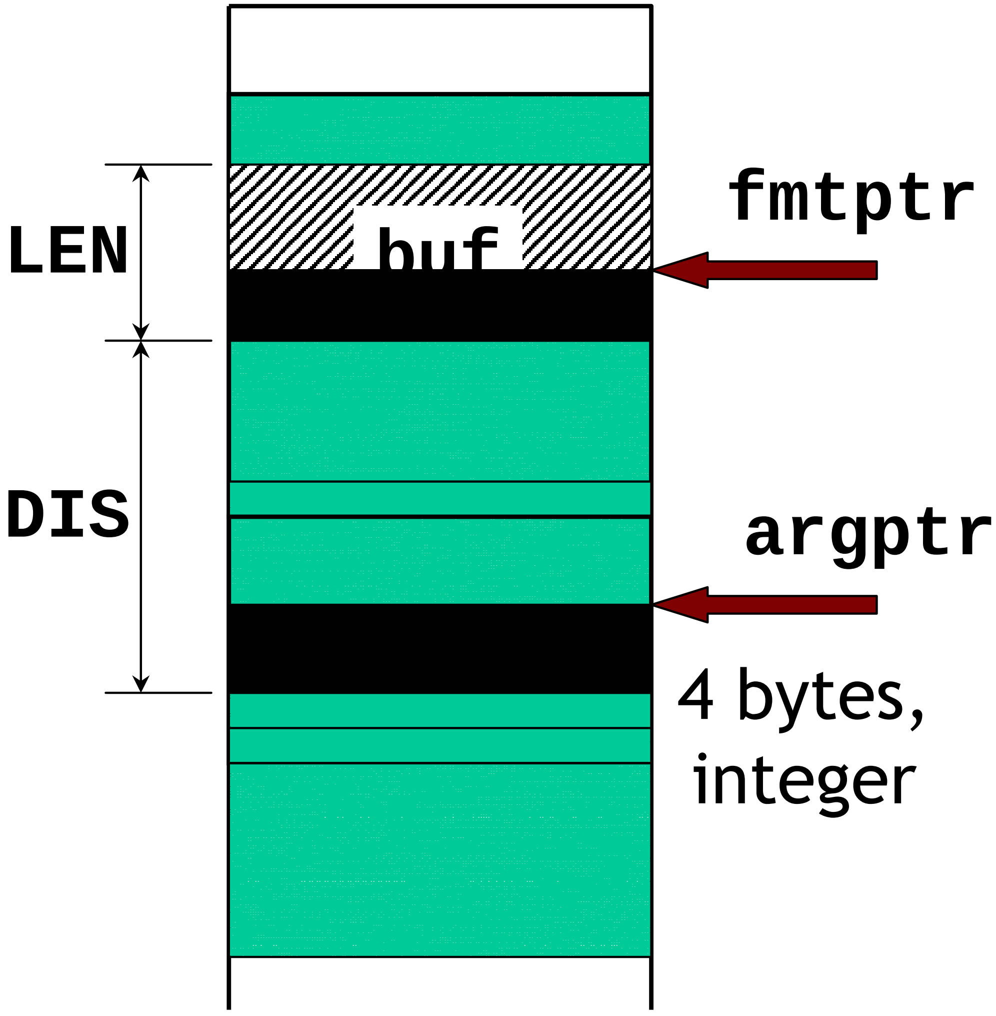

buf = “🟥%s”

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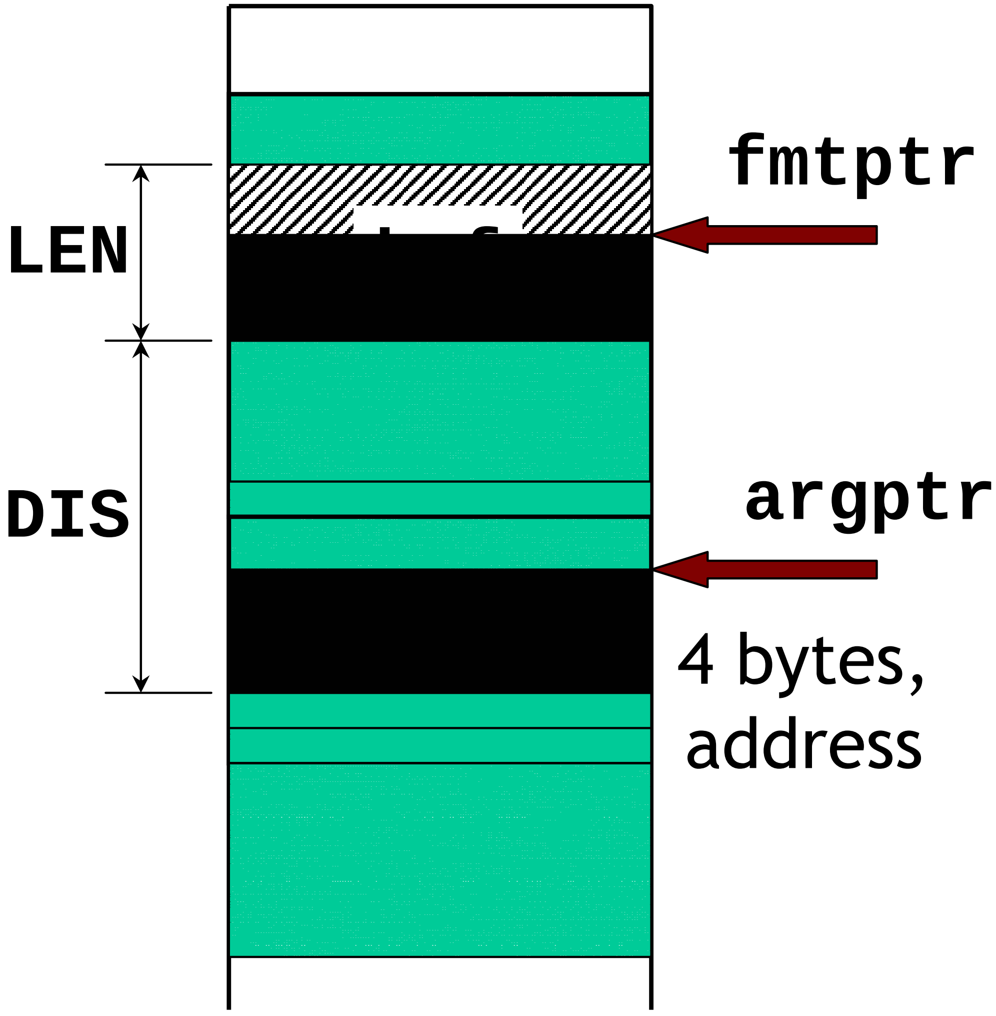
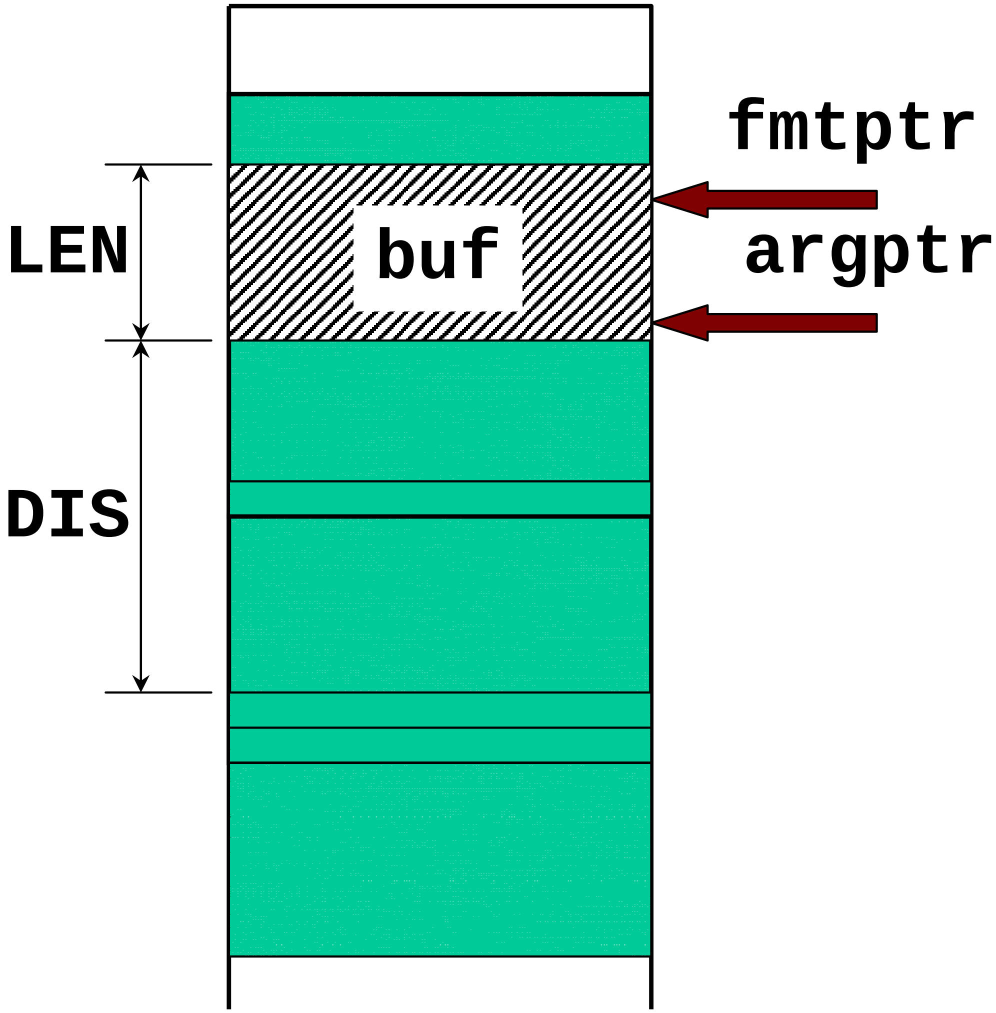


buf = “🟥”

Format-string exploits

What if we move **argptr** into **buf**?

Remember, attacker can control **buf**!



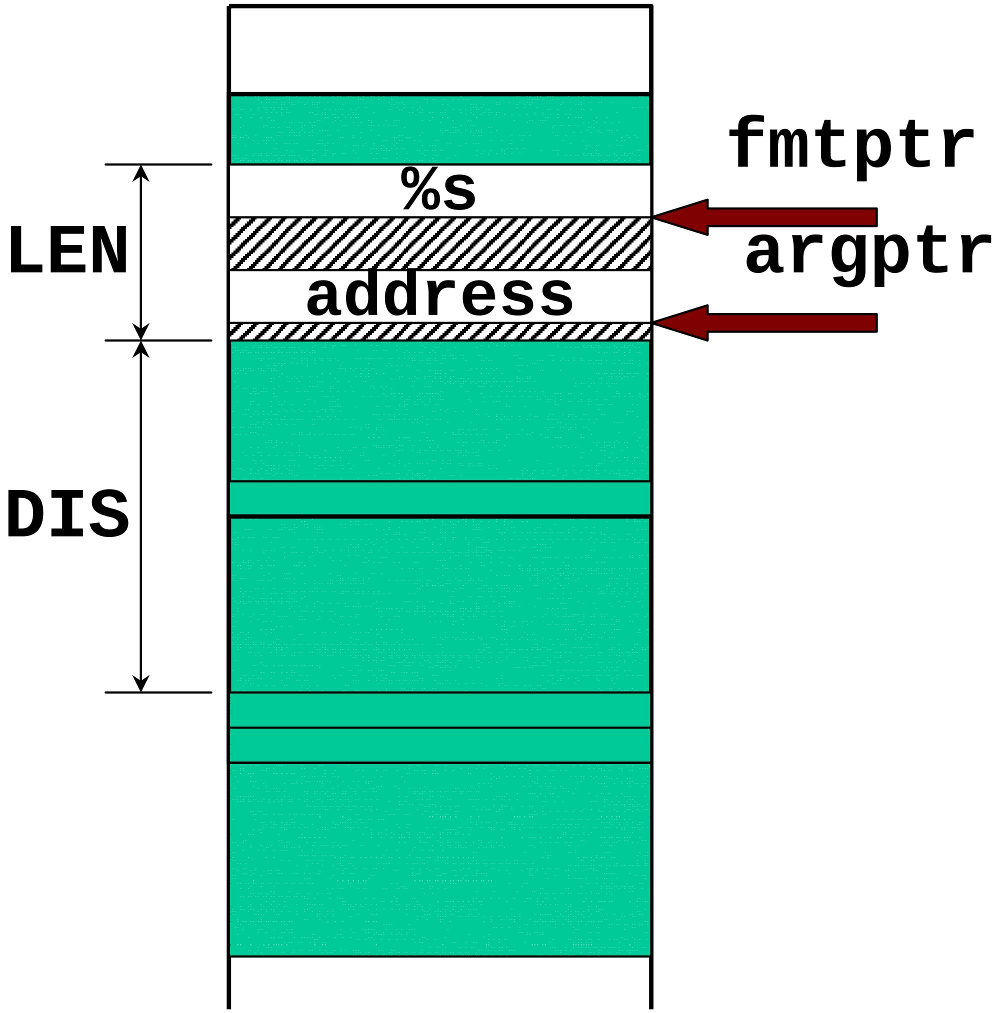
Format-string exploits

Example exploit scenario:

- **fmtptr** is at a “%s”
- **buf** contains an attacker-chosen address.
- **argptr** points to this location within **buf**

Can read from arbitrary memory location!

Can also write to arbitrary memory location, e.g. return addresses (paper has details)

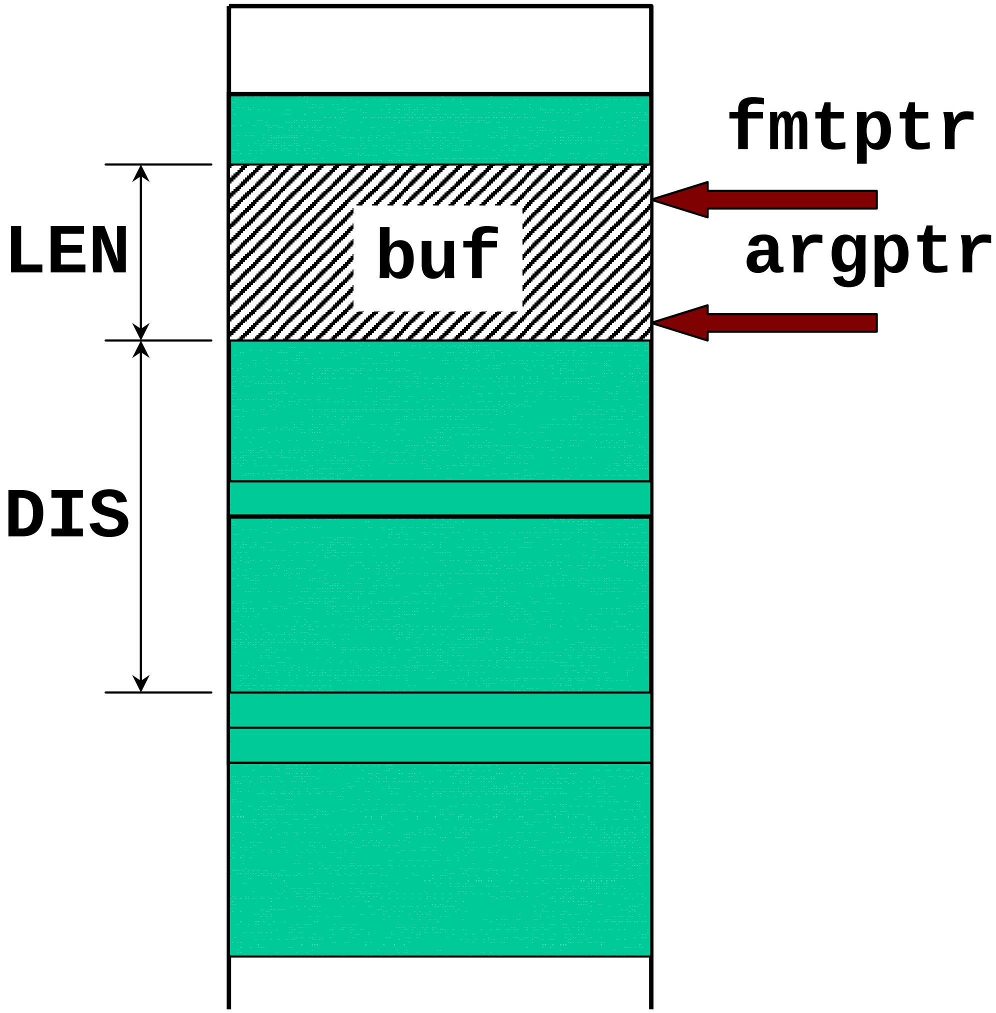


Format-string exploits

Exploit techniques well-known.

Key observations:

1. **DIS** and **LEN** completely characterize any **printf** call.
2. Each byte in **buf** instructs **printf** what to do next.



Format-string exploits

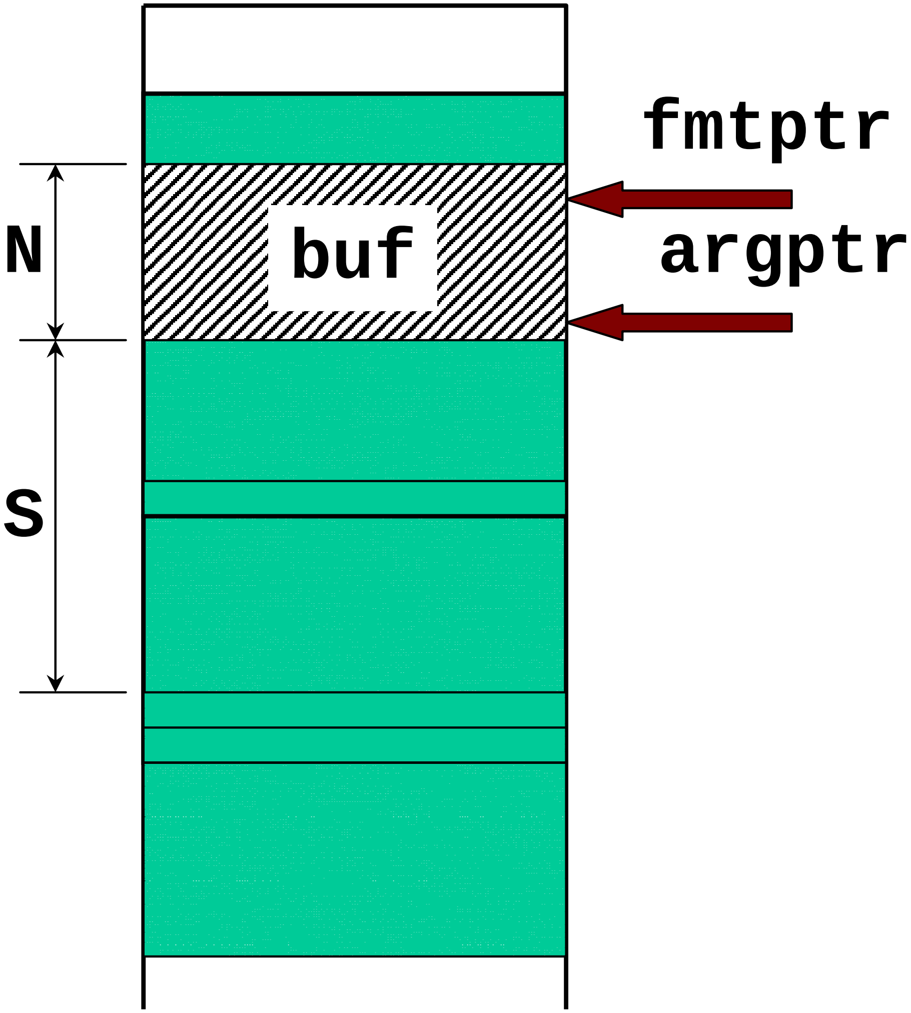
Format-string is a sequence of API operations.

Each byte of the format-string is an instruction.

Finding format-string exploits

=

Finding API-Level exploits



Finding format-string exploits

- Model how **`printf`** interprets format-string:
  - Encoded in the source code of **`printf`**.
  - Need to construct this model only once.
- S = (V,Init,Σ,L)
  - V: Various flags used in **`printf`** implementation that encode its state.
  - Σ: Set of all ASCII characters (size = 256).
  - L: All allowed format-strings (Σ^*)
    - Can restrict L to find exploits that follow a particular pattern

Finding format-string exploits

- For a vulnerable application:
  - Find **`DIS`** and **`LEN`**: How? Disassemble!
  - Formulate Bad.
  - Check against the model of **`printf`**.

- See paper for examples of Bad to:
  - Read from arbitrary memory location.
  - Write to an arbitary memory location.

Finding format-string exploits

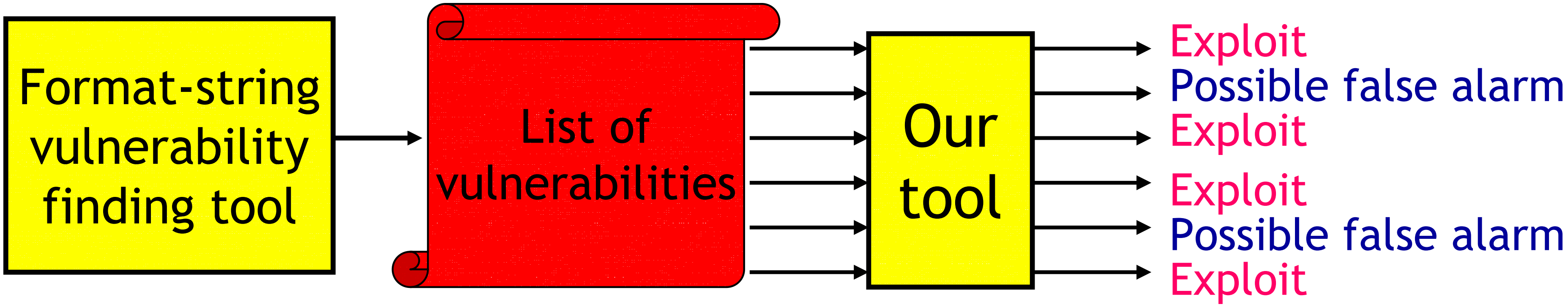
- The model of **`printf`**:
  - Requires precise reasoning about stack locations, in particular, the format-string.
  - Has integer operations: pointer arithmetic to advance **`fmtptr`** and **`argptr`**.
- Quantifier-free Presburger-arithmetic with theory of uninterpreted functions.
  - UCLID tool. [Bryant et al. CAV 2002]

Format-string exploit-detection tool

- Finds exploits against vulnerabilities in real-world software packages.
- Can find different kinds of exploits.
- Can find an arbitrary number of variations of a given exploit.
- Can work on binary executables.
- Can improve the quality of format-string vulnerability-detection tools.

Possible use scenario

- Percent-S [Shankar et al. USENIX Security 2001] finds possibly vulnerable locations. No exploits.
- Run our tool at each vulnerable location:
  - Exploit generated: true vulnerability.
  - No exploit generated: possibly a false alarm.



Results

- Exploits against vulnerabilities in real-world software:
  - See paper for details

Software	DIS	LEN	Exploit description
php-3.0.16	24	1024	Overwrite memory location
qpopper-2.53	2120	1024	Read a memory location
wu-ftpd-2.6.0	9364	4096	Overwrite memory location

Results

DIS	LEN	Read exploit	Write exploit
0	7	“$a_1a_2a_3a_4$%s”	No exploit
4	7	No exploit	No exploit
4	16	“$a_1a_2a_3a_4$%d%s”	“%234Lg%n$a_1a_2a_3a_4$”
4	16	“%Lx%ld%s$a_1a_2a_3a_4$”	“$a_1a_2a_3a_4$%%%229x%n”
8	16	“$a_1a_2a_3a_4$%Lx%s”	“$a_1a_2a_3a_4$%230g%n”
16	16	“%Lg%Lg%s$a_1a_2a_3a_4$”	“$a_1a_2a_3a_4$%137g%93g%n”
20	20	“$a_1a_2a_3a_4$%Lg%g%s”	“$a_1a_2a_3a_4$%210Lg%20g%n”
24	20	“$a_1a_2a_3a_4$%Lg%Lg%s”	“$a_1a_2a_3a_4$%61Lg%169Lg%n”
32	24	“$a_1a_2a_3a_4$%g%Lg%Lg%s”	“$a_1a_2a_3a_4$%78Lg%80g%72Lg%n”

Results

DIS	LEN	Read exploit	Write exploit
0	7	“$a_1a_2a_3a_4$%s”	🟥
4	7	🟥	🟥
4	16	“$a_1a_2a_3a_4$%d%s”	“%234Lg%n$a_1a_2a_3a_4$”
4	16	“%Lx%ld%s$a_1a_2a_3a_4$”	“$a_1a_2a_3a_4$%%%229x%n”
8	16	“a	$a_2a_3a_4$%230g%n”
16	16	“%Lg%Lg%s$a_1a_2a_3a_4$”	“$a_1a_2a_3a_4$%137g%93g%n”
20	20	“$a_1a_2a_3a_4$%Lg%g%s”	“$a_1a_2a_3a_4$%210Lg%20g%n”
24	20	“$a_1a_2a_3a_4$%Lg%Lg%s”	“$a_1a_2a_3a_4$%61Lg%169Lg%n”
32	24	“$a_1a_2a_3a_4$%g%Lg%Lg%s”	“$a_1a_2a_3a_4$%78Lg%80g%72Lg%n”

Ability to find false alarms

Results

DIS	LEN		
0	7	“$a_1a_2a_3a_4$%s”	No exploit
4	7	No exploit	No exploit
4	16	“$a_1a_2a_3a_4$%d%s”	“%234Lg%n$a_1a_2a_3a_4$”
4	16	“%Lx%ld%s$a_1a_2a_3a_4$”	“$a_1a_2a_3a_4$%%229x%n”
8	16		a_4%230g%n”
16	16		%137g%93g%n”
20	20		210Lg%20g%n”
24	20	“$a_1a_2a_3a_4$%Lg%Lg%s”	“$a_1a_2a_3a_4$%61Lg%169Lg%n”
32	24	“$a_1a_2a_3a_4$%g%Lg%Lg%s”	“$a_1a_2a_3a_4$%78Lg%80g%72Lg%n”

Ability to find different kinds of exploits: Parametrized by the predicate Bad

Results

DIS	LEN	Read exploit	Write exploit
0	7	“$a_1a_2a_3a_4$%s”	No exploit
4	7	No exploit	No exploit
8	16	“a_1	$_3a_4$%230g%n”
16	16	“%Lg	$_4$%137g%93g%n”
20	20	“$a_1a_2a_3a_4$%Lg%g%s”	“$a_1a_2a_3a_4$%210Lg%20g%n”
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32	24	“$a_1a_2a_3a_4$%g%Lg%Lg%s”	“$a_1a_2a_3a_4$%78Lg%80g%72Lg%n”

Ability to find variants of an exploit

Talk structure

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- Example: format-string exploit-detector.
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Related work

- Software Model Checking [Blast,SLAM,Magic,CBMC]
  - Counter-example guided abstraction refinement.
  - Exploits ≈ Concrete counter-examples.
- Test generation [Beyer et al. ICSE04,Boyapati et al. ISSTA02]
  - Exploits can be used as test cases.
- Ad-hoc techniques [Thuemmel 2001,Newsham 2000]
  - No soundness guarantees. Cannot find variants.

Summary of important ideas

- Exploit-finding requires modeling low-level details of the system.
- Exploit-finding can benefit vulnerability-finding tools.
- Demonstrated using API-level exploits.

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