3. Coding Errors

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Content

- An overview of typical security-relevant coding errors based on the taxonomy of the 7 (+1) Kingdoms
- A more detailed look at some particular security-relevant coding errors
  - Buffer overflows
  - Dangerous functions
  - Race conditions
- Outlook: More on coding errors will follow later when discussing web application security

Goals

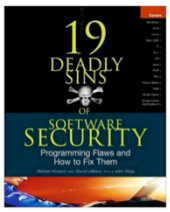
- You know the 7 (+1) kingdoms and can provide some examples about typical errors in each kingdom
- You understand what buffer overflows are, why they happen, how they can be exploited, and how they can be prevented
- You know some dangerous C functions and better suited alternatives for them
- You understand what a race condition is, why they can happen, why they can be security-critical and know some countermeasures to prevent them

Coding Errors (1)

- Experience shows that about 50% of all software vulnerabilities are due to coding errors (bugs)
  - This certainly justifies looking at them in more detail
- There's a wide spectrum of different types of coding errors, but they are usually based on a few fundamental problems
  - → Using some kind of classification scheme is reasonable
- Such a classification scheme helps…
  - To understand and structure the entire problem range better
  - To educate and inform software developers about common coding mistakes that have an impact on security in a structured way and to help them reducing them
  - To provide manuals and guidelines for software developers
  - To integrate the scheme into an automated source code analyzer and provide meaningful reports

Coding Errors (2)

- There exist several classification schemes for security-related coding errors
  - The 19 Deadly Sins of Software Security
  - OWASP Top Ten
  - SANS Top-20
  - CWE/SANS Top 25 Most Dangerous Programming Errors



Common Weakness Enumeration
A Community-Developed Dictionary of Software Weakness Types

- We are using here McGraws Taxonomy of Coding Errors
  - Very general classification scheme, not just for one application domain (such as OWASP)
  - It is continuously maintained and extended
  - Uses a reasonable number of main error classes: 7 (+1) Kingdoms

McGraws Taxonomy of Coding Errors

See *Gary McGraw, Software Security – Building Security In, Addison-Wesley Software Security Series*

The 19 Deadly Sins of Software Security

Michael Howard, David LeBlanc, John Viega, 19 Deadly Sins of Software Security, McGraw-Hill Osborne Media; 1 edition (July 26, 2005)

OWASP Top Ten

http://www.owasp.org/index.php/Category:OWASP_Top_Ten_Project

SANS Top-20

http://www.sans.org/top20

CWE/SANS Top 25 Most Dangerous Programming Errors

http://cwe.mitre.org/top25

7 (+/- 2)

This number stems from psychology research. For most people, the capacity of working memory cannot be increased beyond 7 +/- 2 chunks. However we can enlarge the size of a chunk and thereby increase the number of items in our memory. *George Miller, The Magic Number Seven, Plus or Minus Two. In Psychological Review, vol. 63, pp. 81-97, 1956.*

7 (+1) Kingdoms

7 (+1) Kingdoms of Coding Errors

The 7 (+1) kingdoms of coding errors, in order of importance to software security:

1. Input Validation and Representation
2. API Abuse
3. Security Features
4. Time and State
5. Error Handling
6. Code Quality
7. Encapsulation

* Environment

7 (+1) Kingdoms of Coding Errors

This taxonomy of coding errors continuously grows, as novel problems are uncovered. The taxonomy presented here is also available online

- *http://www.fortify.com/vulncat/en/vulncat/index.html*
- It is continuously extended with new types of coding errors
- It's organized according to programming languages and the kingdoms

It's a good idea to have a look at this website when you are developing an application

Note that due to the sheer amount of different error types in each kingdom, we cannot look into them in a comprehensive fashion. Also note the following:

- Some of the phyla are language dependent (e.g. some library function specific issues in C, catching NullPointerExceptions in Java...)
- Some of the phyla are framework dependent (e.g. validation issues in the MVC framework Struts, bad practices in J2EE applications...)

Kingdom 1: Input Validation and Representation (1)

- Primary problem: user input is not or not correctly validated before it is processed
- The solution is basically quite simple: make sure all input is validated before it is processed
  - Approaches based on white lists are preferable over those using black lists (e.g. define explicitly what is allowed)
  - Example: For a particular form field in a web application, allow at most 20 characters that consist of digits, letters, and space characters
- What makes input filtering difficult is that the same data can be encoded (represented) in different ways
  - It therefore may be possible for an attacker to circumvent a filtering mechanism by encoding the attack data such that only legitimate characters are used

Kingdom 1: Input Validation and Representation (2)

Some examples associated with a lack of input validation:

- Buffer overflows
  - Writing data beyond an allocated buffer can allow an attacker to modify the program flow, crash the program, inject (malicious) own code etc.
- Various injection attacks (command injection, SQL injection, XML injection...)
  - Allows, e.g., execution of malicious commands on behalf of an attacker or execution of arbitrary SQL statements in the backend database
- Cross-site scripting
  - Allows an attacker to execute JavaScript code in the browser of another user to steal credentials, hijack a session etc.
- Path traversal
  - May allow a user to access arbitrary files on the target computer

Kingdom 2: API Abuse

- API (application programming interface) abuse means a programmer…
  - …does not use an API (e.g. a function or a method) correctly
  - …makes incorrect assumptions about the offered functionality

Some examples of API abuse:

- Dangerous functions
  - Some functions or methods simply can't be used in a secure fashion and should therefore not be used at all (e.g. `gets` in C)
- Unchecked return values
  - Ignoring a function's return value can cause the program to overlook unexpected situations (e.g. a reference containing NULL instead of referencing a valid object because something went wrong)
- Wrong security assumptions
  - E.g. relying on `gethostbyaddr` in C or `getHostName` in Java to authenticate a remote host (it's relatively easy to modify DNS responses)

Wrong Security Assumptions

The scenario could be as follows:

- A server has a list of client host names that are allowed to access the server
- When a client connects, the server knows its IP address and performs an inverse DNS lookup to get the host name of the client
- If the received host name is on the list of allowed host names, the client is granted access

The problem is that DNS responses can usually be manipulated, which makes it possible to send the server any host name the attacker wishes – so the programmer of the server has made a wrong assumption about the security the functions/methods to perform DNS queries provide.

Kingdom 3: Security Features

- When using security functions (or security features) in your program, a lot can still go wrong
  - If possible, use existing approaches/components/products that have demonstrated to work well in practice
  - Example: Don't try to invent your own cryptographic algorithm or secure communication protocol – you'll most likely fail

Some examples of poor usage of security features:

- Insecure randomness
  - Using poor pseudo random number generators (or seeding secure ones with predictable values) will result in weak key material
- Incomplete access control
  - A program that does not consistently perform access control will likely allow non-privileged users access to restricted functionality and/or data
- Weak encryption
  - Even communication protocols that are considered secure often support older algorithms due to backward compatibility (e.g. DES or MD5 in TLS)

Kingdom 4: Time and State (1)

- Time and State-related issues may happen if multiple systems, processes or threads interact and share data
  - E.g. with distributed systems, multithreading or multiple processes in the same system
- One reason why these problems occur is because humans (developers) think about programs as if they were executing the job manually
  - E.g. the client sends data, it arrives at the server, the server application reads it all from the buffer, processes it...
  - Then the next client sends data, it arrives at the server…
  - In this world, execution of the program steps and handling of multiple tasks is sequential and well-defined and time and state-related issues rarely occur
- But computers work differently:
  - Tasks are not processed one after another, but (quasi-)parallel
  - As a result, problems may occur due to unforeseen interactions between tasks

Kingdom 4: Time and State (2)

Some examples of time and state-related issues:

- Deadlock
  - Poor usage of locking mechanisms can lead to deadlock (and therefore availability problems)
  - A law in Kansas once stated: "When 2 trains approach each other at a crossing, both shall come to a full stop and neither shall start up again until the other has gone."
- File access race condition: TOCTOU (time of check – time of use)
  - The window of time between checking a file property and using the file may be exploited to launch a privilege escalation attack
- Failure to begin a new session upon authentication
  - Using the same session identifier across authentication boundaries (e.g. in a web application) may allow an attacker to hijack authenticated sessions

Kingdom 5: Error Handling

- Error handling concepts of modern languages (e.g. exceptions) are powerful, but they are difficult to implement correctly
  - Introduces a second control flow, jumps between exception handlers...
  - As a result, errors are often not handled correctly or not at all

Some examples of error handling issues:

- Empty catch block
  - Ignoring exceptions may allow an attacker to provoke unexpected program behavior
- Overly broad catch block (e.g. catching `Exception` in Java)
  - If the program grows and new types of exceptions are thrown, the new exception types will likely not receive any attention
- Leakage of internal information
  - Error messages sometimes propagate internal information (system state, failed database queries...) to the attacker, which provides information for subsequent attacks

Kingdom 6: Code Quality (1)

- Poor code quality increases the likelihood of erroneous code, which increases the probability that security vulnerabilities creep in

- Poor code quality is caused by the following
  - Unreadable code (very difficult to analyse and maintain)
    - Poor names for variables, methods etc.
    - Too long and too complex classes or methods
    - High coupling among classes
    - Forgetting to remove old code
    - ...
  - Because the developer is not careful enough during programming and does not think about various details, e.g.:
    - I'm allocating a resource – where is it freed again?
    - I'm using these three objects / variables – can I be sure they were in fact initialized before?

Kingdom 6: Code Quality (2)

Some examples of problems associated with code quality:

- Memory leak / exhaustion
  - Memory is allocated but never freed, leading to memory exhaustion – and eventually to the termination of the program
  - May happen explicitly (`malloc` and `free` in C) or implicitly (filling a `StringBuffer` in Java until all memory assigned to the JVM is used up)
- Unreleased resource
  - A program that fails to release system resources (file handlers, sockets...) may exhaust all system resources and fail to function properly
- Null dereference
  - A program dereferences a null pointer, which usually results in program termination
  - Often a consecutive fault due to another mistake, e.g. because the programmer hasn't checked the return value of a method or function

Kingdom 6: Code Quality (3)

- Uninitialized variable
  - A program that uses a variable before it has been initialized may result in unpredictable behavior
  - Today, compilers often warn about this, but warnings are easily ignored (which you never should do, warning nearly always make sense!)

- Deprecated code
  - Many programming languages contain deprecated classes, methods or functions, which should no longer be used for various reasons
    - New naming conventions, poor interface design, but also due to security flaws!
  - Using deprecated classes, methods or functions hints at neglected code
  - Compilers usually warn about the usage of deprecated components
    - Always try to get rid of the deprecated component by replacing it – a newer variant is usually available

Deprecation for Security Reasons

An example are some methods of the Java Thread class, which were deprecated because using them makes it virtually impossible to implement multithreaded programs in a secure way. For details, see *http://docs.oracle.com/javase/1.4.2/docs/guide/misc/threadPrimitiveDeprecation.html*.

Another example is the C function gets(), which is also considered to be deprecated due to security reasons. A better alternative is the getline() function.

Kingdom 7: Encapsulation

- Encapsulations is about having strict boundaries between users, programs, and data
  - E.g. make sure that one user of a web application cannot access the data of another current user

Some examples of problems associated with encapsulation include:

- Wrong usage of hidden form fields
  - Hidden fields are basically a useful feature to include data in a web form that should not be visible by the user
  - But don't use hidden fields in web forms to store important session information – it can easily be read and manipulated by an attacker
- Cross-Site Request Forgery
  - Allows an attacker to make arbitrary HTTP requests in another users authenticated web session unless this explicitly prevented (e.g. by using a user-specific secret/token)

Mobile Code in Web Pages

Such code is usually restricted by techniques and concepts such as sandboxing or the same origin policy. The same origin policy is an important security concept for a number of browser-side programming languages, such as JavaScript. The policy permits scripts running on pages originating from the same site to access each other's methods and properties with no specific restrictions, but prevents access to most methods and properties across pages on different sites.

Hidden Form Fields

Imagine a web application that uses a hidden field to remember the authorization level of the user (e.g. guest, registered user, administrator). Whenever a request is received, the web application checks if the authorization level is high enough to perform the requested operation. This can easily be exploited by the attacker to elevate his privileges by making sure the value is set to administrator in every request he makes (which can easily be automated using the appropriate tools). In general, session state information should only be maintained on the server, which effectively prevents such attacks.

Kingdom *: Environment

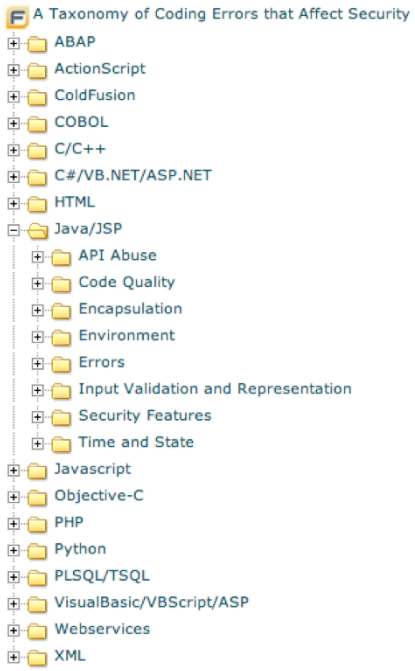
- The software you write does not run by itself, but usually relies on other software
  - Compilers, operating systems, execution environments (JVM, .NET...)
  - Libraries, other software on other computers (in a networked environment), network services (DNS...),...
- The environment includes all of the stuff that is outside of your code but still critical to the security of the software you create

Some examples of problems associated with the environment:

- Insecure compiler optimization
  - Improperly removing (overwriting) sensitive data (e.g. a password or secret key) can compromise security
- Issues with respect to web application frameworks
  - Insufficient session-ID length or randomness (may allow session-ID guessing attacks)

Further Information about Coding Errors

- The taxonomy presented here is available online
  - http://www.hpenterprisesecurity.com/vulncat/en/vulncat/index.html
  - It's organized according to programming languages and the kingdoms
  - It is continuously maintained and extended with
    - new types of coding errors as new attack variants are uncovered
    - new programming languages when they become popular
- It's a good idea to have a look at this information when you are developing an application



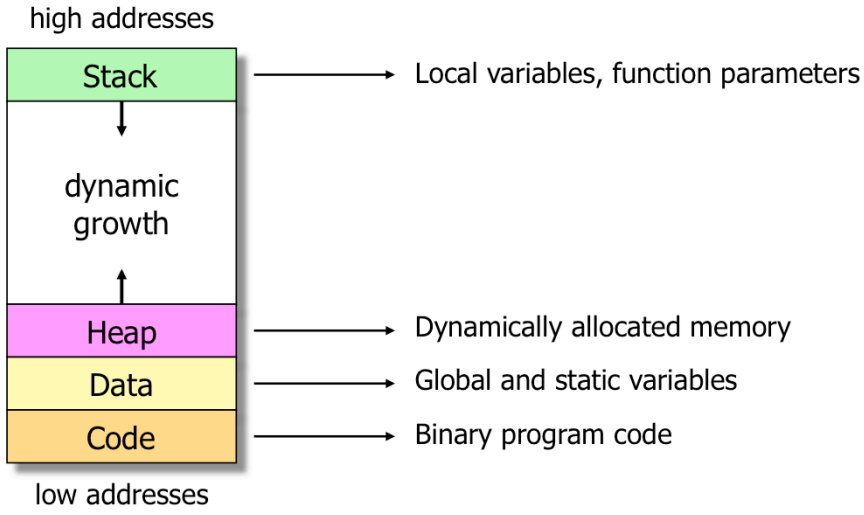
Buffer Overflows

Buffer Overflows

- Buffer overflow attacks exploit programming bugs
  - Fundamental problem: A program writes data submitted by a user/ attacker beyond the end of an allocated buffer in memory
  - Allows an attacker to modify the program flow, crash the program, inject (malicious) own code etc.
  - Part of the "Input Validation and Representation" kingdom
- Despite advances with respect to countermeasures, buffer overflow attacks are still frequently used and many prominent malware incidents (past & present) exploited buffer overflow vulnerabilities:
  - 1988: Morris worm, 2001: Code Red, 2003: SQLSlammer...
  - ...2010: Stuxnet, 2012 Flame
- To understand buffer overflow attacks, one must understand the memory layout of a process and how the stack is used

Typical Memory Organisation

- Every process runs in its own virtual address space
- The address space of a process can be separated into segments



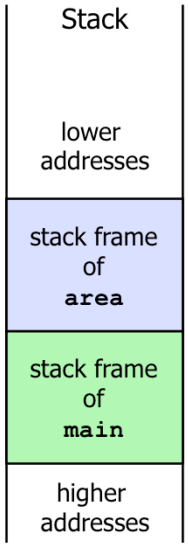
Memory layout of a Process

- The **Code** segment (often also called Text segment) contains the executable program (in machine language). This is where the instruction pointers should normally point to.
- The **Data** segment contains all data, that exist exactly once during program executions (static and global variables).
- The **Stack** segment contains data, that are produced and destroyed dynamically during run-time in a “well-defined order”. This includes function arguments and local variables.
- The **Heap** segment is used for all other, dynamically during run-time generated data (malloc in C, new in Java)

The Stack

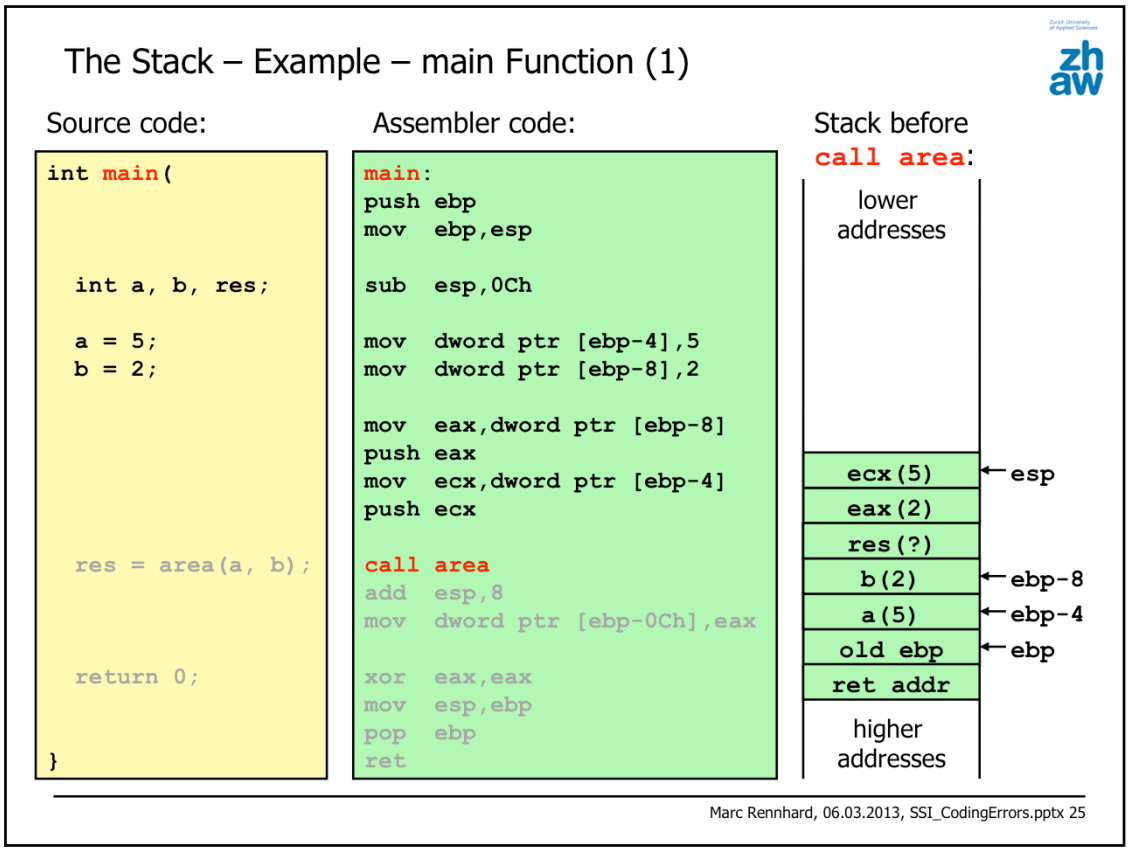
- The "most prominent" place to carry out buffer overflow attacks
- Simple example in C:

```
int area(int length, int width) {
  int scale;

  scale = 3;
  return (scale * length * width);
}

int main() {
  int a, b, res;

  a = 5;
  b = 2;
  res = area(a, b);
  return 0;
}
```



The Stack and Stack Frames

During program execution, a stack grows and shrinks. The stack grows from higher to lower addresses, which means from bottom to top in the illustration above. When the program is started and `main` is called, a **stack frame** for `main` is created. A stack frame belongs to a function and is used when the function is executed. When `main` calls another function `area`, a new stack frame is created and used by `area`. When execution of `area` completes, the stack frame of `area` is removed from the stack and program execution continues in the `main` function (which called area) using again its own stack frame. At any time, only the topmost stack frame is "in usage" by the function that is currently executed.



Base and Stack Pointers

There are two important pointers (CPU registers) associated with the stack. The **stack pointer** (esp) point always to the topmost entry on the stack. It is used to indicate where data shall be pushed onto the stack or popped from the top of the stack. The **base pointer** (ebp) always points to the bottom of the currently used stack frame (not exactly the bottom, but one position above the return address, see below). It remains constant even if the stack frame grows and shrinks and is therefore used to relatively address all other positions in the current stack frame.

main Function until `call area`

In a C program, the main function is the entry point. The executable file that was built during compiling and linking contains additional code (this is not shown here), which basically passes command-line arguments to the main function and calls the main function by executing a `call main`. This is where we start looking at the assembler code of the example program at what happens with the stack in more detail.

Whenever a function is called, the current value of the **instruction pointer** (eip) is put automatically onto the stack by the CPU. This value corresponds to the address to return to after execution of the called function (therefore we call it `ret addr` in the illustration of the stack above). So when the main function that is called by the code that was automatically added to the executable file terminates (using the `ret` instruction, see later), program execution returns to the address that directly follows `call main` in this automatically added code.

The following happens in the main function until `call area` is executed:

- **push ebp** The base pointer of the previous stack frame (the automatically added code that calls the main function) is pushed onto the stack, so it can be regenerated later.
- **mov ebp,esp** The value of the stack pointer is copied to ebp, so ebp points to the bottom of the new stack frame.
- **sub esp,0Ch** esp is moved 12 bytes (C in hex) so there's room for the three int-values a, b and res.
- **mov dword ptr [ebp-4],5** The value 5 (of a) is inserted at the position ebp-4. Note that we assume here that the variables are put onto the stack in the order they are listed in the code, which is the case with many compilers, but which does not necessarily have to be this way. In fact, one can imagine any order; it's up to the compiler to arrange them – and to keep track which variable is located where.
- **mov dword ptr [ebp-8],2** The value 2 (of b) is inserted at the position ebp-8.

The following four instructions are used to pass the parameters (a and b) to the function `area`. In C, parameters are passed via the stack in opposite order of the parameter list (first b, then a).

- **mov eax,dword ptr[ebp-8]** The content of ebp-8 (b) is copied into register eax.
- **push eax** The value in eax (b) is pushed onto the stack (second function parameter).
- **mov ecx,dword ptr[ebp-4]** The content of ebp-4 (a) is copied into register ecx.

The Stack – Example – area Function

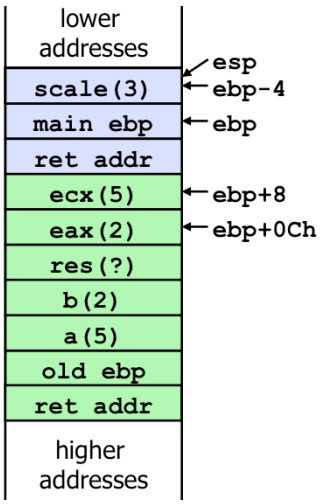
Source code:

```
int area(
  int length,
  int width) {

  int scale;

  scale = 3;

  return (scale *
  length * width);



}
```

Assembler code:

```
area:
push ebp
mov  ebp,esp

sub  esp,4h

mov  dword ptr [ebp-4],3

mov  eax,dword ptr [ebp-4]
imul eax,dword ptr [ebp+8]
imul eax,dword ptr [ebp+0Ch]

mov  esp,ebp
pop  ebp
ret
```

Stack during `call area`:



- After returning from the **`area`** function:
  - The return value is stored in register eax
  - The area stack frame has been removed
  - Program execution continues in main after the **`call area`** instruction

Marc Rennhard, 06.03.2013, SSI_CodingErrors.pptx 26

area Function

Like with the main function, the current value of the instruction pointer (eip) is put automatically on the stack by the CPU when `call area` is executed. Here, eip corresponds to the address of the instruction add esp,8 in the main function, which is the instruction directly following the `call` instruction and which is the first instruction that will be executed when returning to the main function. The following happens during execution of the area function:

- **push ebp** The base pointer of the previous stack frame (the one of the main function) is pushed onto the stack, so it can be regenerated later.
- **mov ebp,esp** The value of the stack pointer is copied to ebp, so ebp points right above the stored return address in the new stack frame.
- **sub esp,4h** esp is moved 4 bytes so there's room for the int-variable scales.
- **mov dword ptr[ebp-4],5** The value 3 (of scale) is inserted at the position ebp-4.

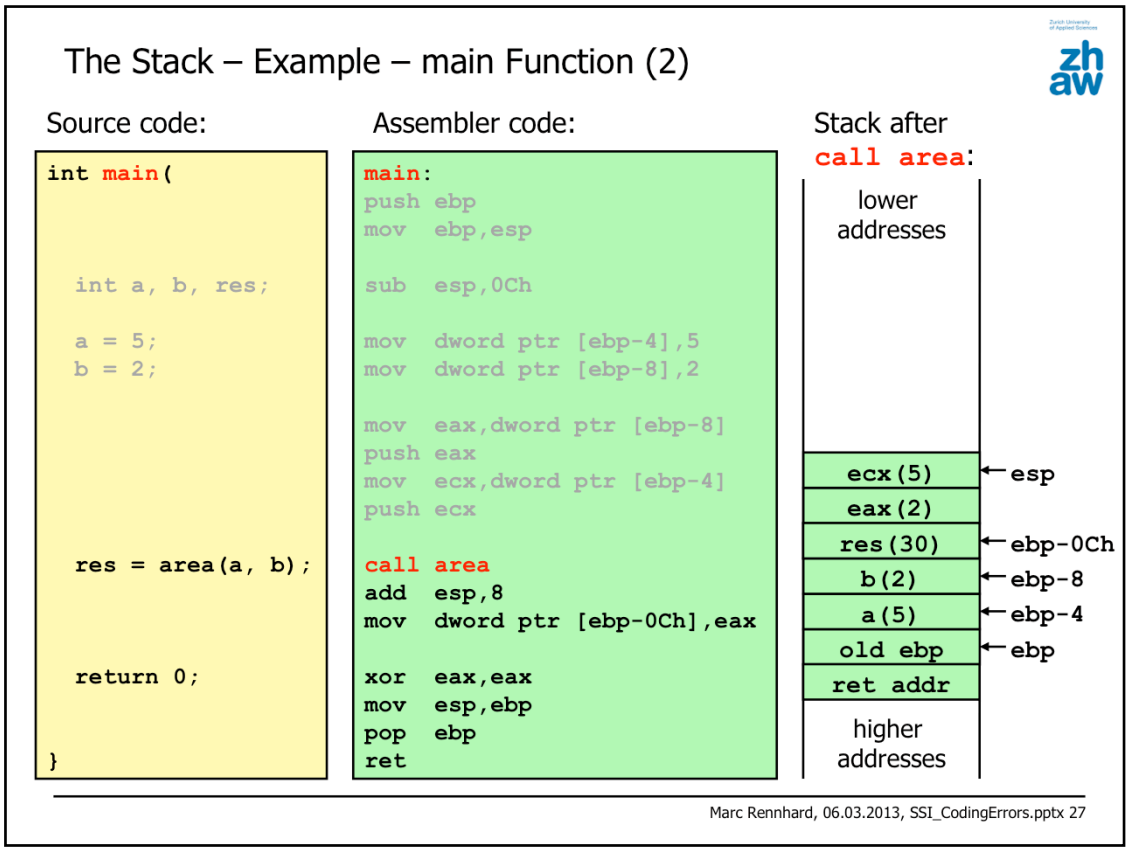
The following three instructions build the product scale * length * width. Register eax is used to carry out the computation, because eax is used to return a value from a function.

- **mov eax,dword ptr[ebp-4]** The content of ebp-4 (scale) is copied into register eax.
- **imul eax,dword ptr[ebp+8]** The content of ebp-8 (length) is multiplied with the value in eax; the result is put into eax.
- **imul eax,dword ptr[ebp+0Ch]** The content of ebp-12 (width) is multiplied with the value in eax; the result is put into eax.

Finally, the stack frame is "removed" by moving esp to the appropriate position and by copying the main ebp value into ebp, so program execution can resume after the call instruction that was used to jump to the area function.

- **mov esp,ebp** The value of the base pointer is copied to esp, so esp points right above the return address in the current stack frame. Everything above the new value of esp has therefore been "removed" from the stack.
- **pop ebp** Copy the topmost value of the stack (main ebp) into ebp and move esp one position down.
- **ret** Copy the topmost value of the stack (ret addr) into the instruction pointer eip and move esp one position down.

Now, the stack looks exactly as it has before executing call area in the main function. The return result is



area Function after `call area`

When returning from the area function, program execution continues at the instruction add esp, 8:

- **add esp,8** This increments the stack pointer by 8, i.e. moves it two positions down. This is done to remove the function parameters, which were put onto the stack by the main function before calling the area function.
- **mov dword ptr [ebp-0Ch],eax** The value eax (the return value of the area function) is copied to the position ebp-12 (res).

The following four instructions are used to return the value 0 (which in C means “normal program termination”) to the automatically added code to the main function. Again, the return value is passed using register eax. The last three instructions are the same as used in the area function; in fact, these three instructions are always used to return from a function.

- **xor eax,eax** This is an efficient way to write the value 0 into eax.
- **mov esp,ebp** The value of the base pointer is copied to esp, so esp points right above the return address in the current stack frame. Everything above the new value of esp has therefore been “removed” from the stack.
- **pop ebp** Copy the topmost value of the stack (old ebp) into ebp and move esp one position down.
- **ret** Copy the topmost value of the stack (ret addr) into the instruction pointer eip and move esp one position down.

Now, all stack entries added by the main function have been removed again. Program execution continues after call main in the automatically added code, which basically terminates the program and returns the return value (0) to the environment that started the program (e.g. a shell)

Why do Buffer Overflows happen? (1)

- Buffer overflows can only happens with languages such as C, C++ that do not check array boundaries during runtime
- With languages/environments such as Java and .NET, it is not possible to write a program that itself has a buffer overflow vulnerability
  - Because the runtime environment (e.g. JVM) checks every array access and makes sure it happens "within the array boundaries"
  - Access beyond array boundaries is prevented (e.g. `ArrayIndexOutOfBoundException`)
- But: the underlying virtual machine (usually written in C or C++) may actually contain buffer overflow vulnerabilities (this has happened)
  - Which may allow an attacker to write a specifically crafted Java program which exploits the vulnerability to get, e.g., access to the underlying operating system

Why do Buffer Overflows happen? (2)

- This works in C without compile/runtime-error:

```
void function() {
  char sBuf[12];
  char lBuf[24] = "A looooooooooong string!";

  strcpy(sBuf, lBuf);  /* Copies lBuf to sBuf */
}
```

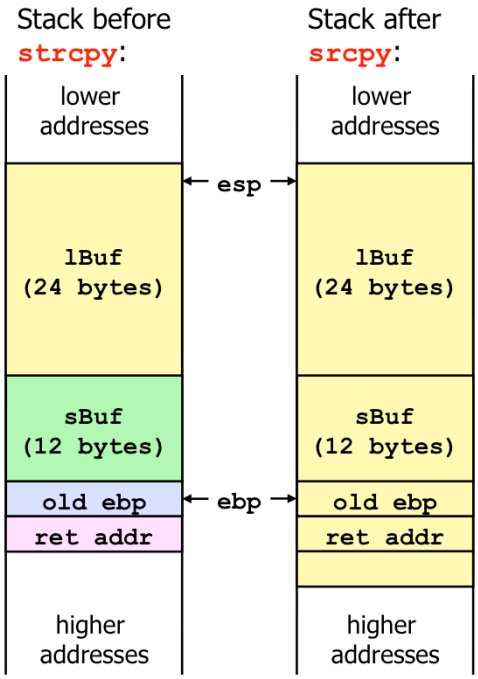
  - In C, local array variables are stored on the stack (unlike Java)
  - Copies the 24 characters from `lBuf` into the 12-character array `sBuf`
  - This simply overwrites the 12 characters following `sBuf` on the stack
  - Overflows the buffer `sBuf` → therefore the name buffer overflow

No Buffer Overflows in Java/.NET?

As the runtime system checks whether access to e.g. arrays cannot be made beyond the boundaries, it is not possible to write a program that itself has a buffer overflow vulnerability. However, here may be (in fact, this has happened) vulnerabilities in the underlying runtime systems (often written in C or C++), which may allow an attacker to write a specifically crafted Java program which exploits the vulnerability, to get, e.g., access to the underlying operating system.

Effect on Program Execution

- 24 bytes from `lBuf` are written into `sBuf`
- This overwrites `old ebp`, `ret addr` in the current stack frame (and an additional 4 bytes)
- When returning from `function`, the program jumps to what is stored in `ret addr`
- This is not what was originally stored there → arbitrary behaviour
- Probably: segmentation fault as the CPU likely tries to access memory locations it is not allowed to access



How to Exploit a Buffer Overflow (1)

- The previously discussed buffer overflow cannot be exploited by an attacker, as a fixed string is copied
  - Will probably easily be detected during testing, as it always occurs when `function` is called
- Much more interesting: buffer overflows, where the user can submit the data to be copied into a buffer
  - Command-line arguments
  - Input submitted to a program that is executed locally
  - Most interesting: input submitted to a program over the network
- Scenario:
  - Networked application, the server gets data (char array) from the client
  - The data is read and processed on the server in a function `processData`
  - The programmer assumes the client sends at most 256 bytes and does therefore not check the input length

Assumption of the Programmer

One can argue the programmer is “quite stupid” to assume the server only gets at most 256 bytes at a time from the client. However, assume that the client program that is used with this server makes sure that no more than 256 bytes are submitted (maybe the programmer has developed it himself) at a time, and in this case, the programmer’s assumption makes sense. The problem is, however, that attackers usually do not use the “official” client programs but directly craft packets they send to the server, which bypasses all client-side security/validation mechanisms.

Just like with the web applications discussed before: never rely on client-side validation to guarantee the format of data submitted by the user; always validate the data when receiving them at the server.

How to Exploit a Buffer Overflow (2)

```
void processData(int socket) {
  char buf[256];
  char tempBuf[12];
  int count = 0, pos = 0;

  /* Read data from socket and copy it to buf */
  count = recv(socket, tempBuf, 12, 0);
  while (count > 0) {
    memcpy(buf + pos, tempBuf, count)
    pos += count;
    count = recv(socket, tempBuf, 12, 0);
 }

  /* Do something with buf */
  ...

  /* Return */
}
```


Reading data from a Socket

A few explanations to the loop that reads data from the socket:

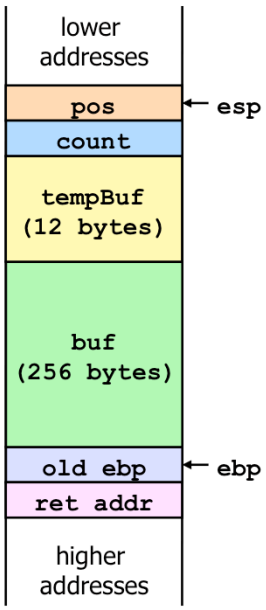
- **count = recv(socket, tempBuf, 12, 0)** reads at most 12 bytes from socket and copies them into `tempBuf`. It also writes the number of bytes read into `count`. If there are no more bytes to read, the function returns 0. The fourth parameter is set to 0 because we do not use any special flags that could also be passed to the function. Note that no buffer overflow can happen here because at most 12 bytes are read from the socket at a time.
- **memcpy(buf+pos, tempBuf, count)** copies the first `count` bytes from `tempBuf` into the array `buf`. The bytes are copied into positions `pos`, `pos+1`, …, `pos+count-1` of `buf`.

The while-loop continues to read data from the socket and copies it into `buf` until there's no more data from the client to read (`recv` returns 0). It doesn't matter whether the user has entered 5 or 5000 bytes, the function processData simply copies them into the 256-byte buffer `buf`.

How to Exploit a Buffer Overflow (3)

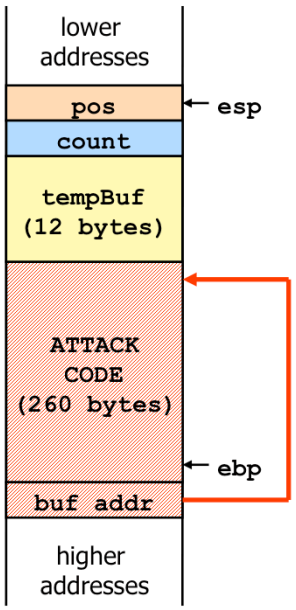
- What happens if more than 256 bytes are sent by the client
  - the 257th - 260th bytes overwrite `old ebp`
  - the 261st - 264th bytes overwrite `ret addr`
- A user accidentally submitting more than 256 bytes of data will probably "just" crash the server program
- An attacker can do the following:
  - Submit 264 bytes data
  - The first 260 bytes contain code crafted by the attacker
  - The 261th - 264th bytes contain the address of `buf`
  - If the function is left (`ret`), program execution jumps to the start of `buf` and executes the code submitted by the attacker!

Stack frame layout:



How to Exploit a Buffer Overflow (4)

Stack frame layout after code injection:



- The attacker can insert any code that fits into the available memory range:
  - Access the local file system
  - Create a user account
  - Spawn a new process
  - Download and install software (malware/ spyware/backdoor…)
  - …
- The inserted code is run with the privileges of the exploited program
  - This is one reason you should run software with minimal privileges

Marc Rennhard, 06.03.2013, SSI_CodingErrors.pptx 34

Crafting a Buffer Overflow Attack

Discovering a buffer overflow vulnerability and crafting a corresponding attack is certainly not easy, especially if the attacker does not have access to the source code or at least a local version of the program code to experiment with. In general, finding and exploiting buffer overflow attacks without having access to the source code involves a lot of trial-and error. Buffer overflow vulnerabilities can be found by simply "throwing" various different inputs at a program and waiting until it crashes. If it crashes, it's likely a buffer overflow occurred that corrupted the stack and caused a segmentation fault. The next step is then to learn more about the stack layout, but again, this is difficult without a debuggable version of the program.

For instance, in the example above, learning the exact memory address of the buffer `buf` on the stack is difficult. However, this is needed because the attacker must overwrite the return address of the stack frame with the address of `buf`. One trick that is often used by attackers to make life easier is to insert several `nop` (no operation) instructions at the beginning of `buf` and only then the code. `nop` instructions are executed but basically do nothing (besides consuming CPU-cycles). If the attacker inserts 100 `nop` instructions, he can not only use the correct address of buf, but any address in the range `buf…buf+99` (on a x86-based CPU, a `nop` instruction is 1 byte long) to overwrite the return address and the attack will be successful.

Sometimes, "black hats" (the bad guys) also get help from the "white hats" (the good guys, ethical hackers) who discover a buffer overflow vulnerability and publish a non-malicious proof-of-concept exploit of the attack. While this is certainly a good idea to put pressure on the software manufacturer to quickly release a patch and to increase the quality of their software in the future, it also gives the attacker a good basis to exploit the vulnerability in a malicious way. Whether publishing discovered vulnerabilities is a good idea or not has been and still is discussed extensively by security experts, although today, most believe it's indeed a good idea. In the foreword of the book "Hacking Exposed, 2nd Edition", Bruce Schneier, a well-respected security professional, argues why publishing vulnerabilities is a good idea.

Security that is based on publishing vulnerabilities is more robust. Yes, attackers learn about the vulnerabilities, but they would have learned about them anyway. More importantly, defenders can learn about them, product vendors can fix them, and sysadmins can defend against them. The more people that know about a vulnerability, the better chance it has of being fixed. By aligning yourself with the natural flow of information instead of trying to fight it, you end up with more security rather than less.

- *Source: http://www.hackingexposed.com/Foreword/foreword2.html*

Buffer Overflows – Countermeasures (1)

- Good programming techniques
  - Make sure buffer overflows don't happen by checking the length of submitted data (input validation)
  - Avoid unsafe C/C++ functions (e.g. **`gets`**) and use the corresponding safer alternatives whenever possible (e.g. **`fgets`**)
- Automated software tests
  - Static code analysis
  - Fault injection: submit various inputs and analyse program behaviour
- Compiler checks and extensions
  - Some compilers can insert additional code to check boundaries when data is copied into a buffer, but this is only possible if the compiler can determine the buffer size
  - Stack-canaries to prevent overwriting of the return address

Personal Firewalls

"Normal" computer users can already do a lot to protect their systems from buffer overflow attacks by using a personal firewall and blocking any access from outside to local services because client systems rarely have to provide services to other computers. If needed, one can always selectively grant access to some services. Especially, on MS Windows systems, block access to TCP ports 135-139 and 445 (unless you really must provide access to them) as the corresponding services have a long history of buffer overflow vulnerabilities.

Compiler Checks and Extensions

A stack-canary means that the compiler inserts code into the functions of the program that puts a random value (the "canary", generated at the start of the program) onto the stack right after the return address whenever a function is called. In addition, the inserted code checks if the canary was not changed before returning from the function. The idea is that if a buffer overflow vulnerability is exploited to modify the return address, this most likely also results in an overwritten canary. If the code determines a canary has been changed, the program terminates immediately.

The gcc compiler offers several options that help preventing buffer overflow attacks. The option -fstack-protector advises the compiler to insert stack-canaries. The Option -D_FORTIFY_SOURCE=2 tells the compiler to insert boundary checks (if possible) around potentially critical operations such as buffer copying.

An interesting article about protection against buffer overflow attacks was published in the *c't Magazin für Computertechnik, 17/2006*.

Buffer Overflows – Countermeasures (2)

- No eXecute (NX) bit / eXecute Disable (XD) (SPARC, IA64, AMD64…)
  - Disallows executing program instructions in certain memory areas (stack)
  - Specified in the paging table (mapping virtual to physical memory) using one of the 64 bits
  - E.g.: part of Linux kernel since 2.6.7
- Address Space Layout Randomisation (ASLR)
  - Randomises the address layout of a process when it is loaded, e.g. part of Linux kernel since 2.6.12, is constantly improved
  - Causes the segments (code, heap, stack…) to be placed at non-predictable locations in the virtual memory space
  - Prevents an attacker from predicting the address layout, which is a prerequisite for many buffer overflow attacks
  - Works against a wide variety of buffer overflow attacks that go beyond inserting code into the stack, such as:
    - Manipulate program flow only by overwriting the return address
    - Only overwrite a pointer variable such that it points to a different address
    - Exploit memory organisation on the heap

So is the Buffer Overflow Problem solved?

Looking at all the features offered by compilers and operating systems, can we conclude the buffer overflow problem is solved? No! First of all, there's no requirement for these features to be enabled – software you have developed and deployed will run independent of whether the features are used or not. Second, modern (mobile) platforms may not offer such protection features in all cases yet. Third, new buffer overflow techniques are continuously published that sometimes make the protection features useless or at least reduce their effectiveness. As a result, it's still important that you try to prevent buffer overflow vulnerabilities in your code and consider the protection techniques as a second line of defence (defence in depth). Note that the CVE statistics (*http://web.nvd.nist.gov/view/vuln/statistics*) shows that buffer overflow vulnerabilities are still very frequent, but exploiting them has become more complicated due to the technical protection measures.

Dangerous Functions

Dangerous Functions (1)

- Notably in C and C++, some functions are dangerous to use and should be avoided
- Many of these functions work on strings (in C, this is a char array terminated with a null byte) and are prone to buffer overflows
- Part of the "API Abuse" kingdom
- Example:

```
char *gets(char *s);
```

The *gets()* function shall read bytes from the standard input stream, stdin, into the array pointed to by *s*, until a <newline> is read or an end-of-file condition is encountered. Any <newline> shall be discarded and a null byte shall be placed immediately after the last byte read into the array.

gets

For a description, see: *http://www.opengroup.org/onlinepubs/009695399/functions/gets.html*

Dangerous Functions (2)

- Consider the following simple program that uses `gets`:

```
#include <stdio.h>

main() {
  char buffer[25];
  printf("\nEnter Text : ");
  gets(buffer);
}
```

- What happens if we enter 10 or 25 characters?

```
rennhard@ubuntu-generic:~$ ./gets

Enter Text : 1234567890
rennhard@ubuntu-generic:~$ ./gets

Enter Text : 12345678901234567890123 45
*** stack smashing detected ***: ./gets terminated
```

10 characters OK (requires 11 bytes in buffer)

25 characters NOK (requires 26 bytes in buffer)

Note: The first of the canary bytes may be zero (e.g. with gcc 4.6), so the above example with 25 characters may not always trigger “stack smashing detected”. Using 26 characters usually works.

Dangerous Functions (3)

- The example on the previous slides also shows that gcc (on Ubuntu) per default has the stack protection feature enabled
  - gcc uses a stack canary approach
  - That's why it states "stack smashing detected"

- Disabling the feature results in a "normal" segmentation fault, which is a typical result of a buffer overflow

```
rennhard@ubuntu-generic:~$ gcc -fno-stack-protector -o gets gets.c
/tmp/ccEte5v3.o: In function `main':
gets.c:(.text+0x24): warning: the `gets' function is dangerous and should not be
 used.
rennhard@ubuntu-generic:~$ ./gets

Enter Text : 123456789012345678901234 5
Segmentation fault
```

  - Sidenote: Depending on the used version, the compiler may issue a warning about using `gets`

Dangerous Functions (4)

- That's great news – we have stack canaries so there's no need to avoid unsafe functions such as `gets`
- Nope, because…
  - The stack canary is only included during compilation, but one can never know what compiler is going to be used with what options
  - There may be flaws in the stack canary approach that can be used to defeat it (e.g. if the canaries can be predicted by the attacker)
  - The program still crashes when a buffer overflow occurs, which leads to availability problems
- As a result, the only truly secure way is get rid of the bug where it occurred: in the code
  - Additional security measures such as stack canaries (and other buffer overflow protection mechanism) should therefore only be considered as a second line of defense (i.e. defense in depth)

Dangerous Functions (5)

- A better alternative to using gets is fgets

```
char *fgets(char *restrict s, int n, FILE *restrict
stream);
```

The *fgets()* function shall read bytes from *stream* into the array pointed to by *s*, until *n*-1 bytes are read, or a <newline> is read and transferred to *s*, or an end-of-file condition is encountered. The string is then terminated with a null byte.

- Resulting program:

```
#include <stdio.h>

main() {
  char buffer[25];
  printf("\nEnter Text : ");
  fgets(buffer, 25, stdin);
}
```


Why using fgets when we have stack canaries?

It's always better to truly solve the problem instead of hoping another security mechanism is available that takes care of the problem. The stack canary is only included during compilation, but one can never know what compiler is going to be used with what options and what protection mechanism, so the only truly secure way is preventing the bug in the first place: in the code. Additional security measures such as stack canaries should therefore be considered

fgets

Just like gets, fgets is part of the ANSI C standard library.

For a description, see: *http://www.opengroup.org/onlinepubs/009695399/functions/gets.html*

Dangerous Functions (6)

- But **`fgets`** is far from foolproof and requires that the programmer supplies the correct value for the number of bytes to be read
- Therefore, this program...

```
#include <stdio.h>

main() {
  char buffer[25];
  printf("\nEnter Text : ");
  fgets(buffer, 26, stdin);
}
```

- ...still results in a buffer overflow

```
rennhard@ubuntu-generic:~$ ./fgets

Enter Text : 12345678901234567890123456
*** stack smashing detected ***: ./fgets terminated
```


Note: As mentioned before, the first of the canary bytes may be zero (e.g. with gcc 4.6), so the above example may not always trigger “stack smashing detected”. Using 27 as the second parameter in fgets and entering 26 characters usually works to trigger the detection.

Dangerous Functions (7)

- There exist safer versions for many string functions in C, for instance **`strncpy`** instead of **`strcpy`**

```
char *strcpy(char *restrict s1, const char *restrict s2);
```

The *strcpy()* function shall copy the string pointed to by *s2* (including the terminating null byte) into the array pointed to by *s1*. If copying takes place between objects that overlap, the behavior is undefined.

```
char *strncpy(char *restrict s1, const char *restrict s2,
size_t n);
```

The *strncpy()* function shall copy not more than *n* bytes (bytes that follow a null byte are not copied) from the array pointed to by *s2* to the array pointed to by *s1*. If copying takes place between objects that overlap, the behavior is undefined.

- But in all cases, correctly specifying n is mandatory, otherwise buffer overflows will likely result

strncpy

Just like strcpy, strncpy is part of the ANSI C standard library.

For a description, see: *http://www.opengroup.org/onlinepubs/009695399/functions/strncpy.html*

Race Conditions

Race Conditions

- Race conditions are possible in scenarios where multiple threads or processes are run simultaneously that may potentially interact
  - In such scenarios, race condition bugs are very common
- Race conditions are a very special type of bug
  - Race conditions can easily be overlooked during testing, because they often don't appear in highly controlled testing environments
  - A specific race condition in a program may occur only rarely, which makes them hard to reproduce and debug
  - Fixing them is not always easy
- Most of the time, race conditions present robustness problems, but sometimes, race conditions also have security implications
- Part of the "Time and State" kingdom

Race Conditions

This information here stems from *John Viega, Gary McGraw, Building Secure Software: How to Avoid Security Problems the Right Way, Addison-Wesley Professional Computing*. The book's chapter about race conditions is also available online: *http://www.informit.com/articles/article.aspx?p=23947*.

What is a Race Condition – the "Two Elevators Problem"

- Alice and Bob, working at the same company, agree to meet for lunch in the lobby at noon
  - But they don't agree whether they mean the lobby at their office level or the main lobby
- At 12:15, Alice is waiting for Bob in the office lobby
  - She realizes Bob may be in the main lobby and takes one elevator down
- If Bob's there – good; but if he isn't, Alice can't conclude Bob is late
  - Just like to Alice, it could have occurred to Bob that Alice is waiting in the other lobby, so he may have taken the other elevator to go up
- This is a race condition: The result will only be 100% clear for Alice if we assume Bob does not take the other elevator at the same time

A race conditions occurs when for the correct outcome or behavior
- An assumption must be valid for a period of time...
- ...but it is not guaranteed the assumption is valid in any case

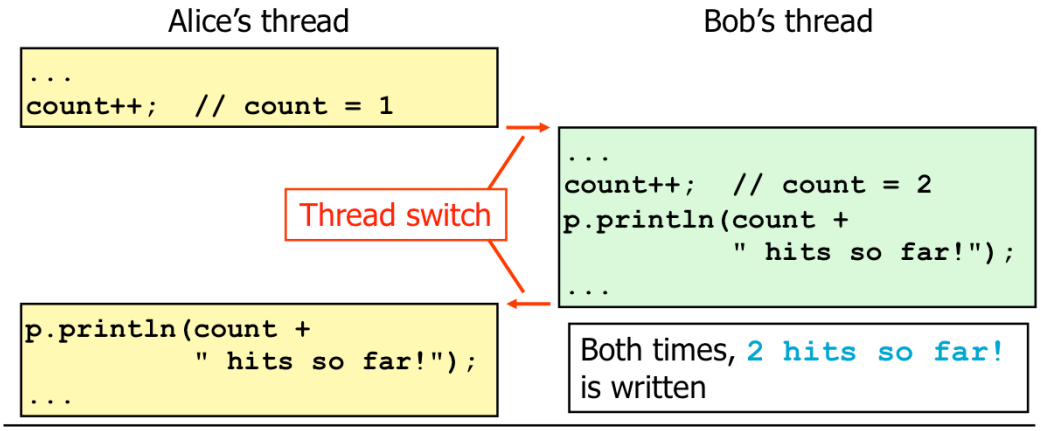
Example: Java Servlet (1)

```
import java.io.*;
import java.servlet.*;
import java.servlet.http.*;

public class Counter extends HttpServlet {
  private int count = 0;

  public void doGet(HttpServletRequest in,
                    HttpServletResponse out)
                    throws ServletException, IOException {
    out.setContentType("text/plain");
    Printwriter p = out.getWriter();
    count++;
    p.println(count + " hits so far!");
  }
}
```

- Question: can you spot a race condition here?

Example: Java Servlet (2)

- The example contains a race condition, because Java servlets are multithreaded
  - Multiple threads that handle requests from different users use the same servlet instance, which may result in a wrong value of `count` being written
- Assume Alice and Bob use the servlet at nearly the same time
  - We assume `count = 0` at the beginning



Servlet Threads FAQ

(From *http://www.codestyle.org/java/servlets/faq-Threads.shtml*)

Q: How does the container handle concurrent requests?

A: Servlet containers usually manage concurrent requests by creating a new Java thread for each request. The new thread is given an object reference to the requested servlet, which issues the response through the same thread. This is why it is important to design for concurrency when you write a servlet, because multiple requests may be handled by the same servlet instance.

Q: Are you saying there is only one servlet instance for all requests?

A: The way that servlet containers handle servlet requests is not prescribed to this extent; they may use a single servlet, they may use servlet pooling, it depends on the vendor's system architecture. New threads are not necessarily created for every servlet request but may be recycled through a worker thread pool for efficiency. The point is that you should write your servlet code to take account of a multi-threaded context regardless of the container implementation you happen to be using. In other words, you should adhere to the principle of write once, run anywhere.

Multiple Threads and Multiple Cores

With multiple cores, threads may run truly parallel, which result in basically the same problem as described above:

- Alice's thread increments count
- Bob's thread increments count
- Alice's thread writes "2 hits so far"
- Bob's thread writes "2 hits so far"

Example: Java Servlet (3)

- The likelihood that the wrong behavior occurs is small
  - It happens only, if a thread switch happens between incrementing `count` and the call of `println`

```
count++;
p.println(count + " hits so far!");
```

- Nevertheless, this is a bug and it should be fixed
  - Even this is no security-critical bug – but similar security-critical bugs can easily be imagined
    - Imagine that instead of updating a count-variable a security token for session tracking is generated and sent to the user
    - If a switch happens between generating a token and sending it to the user, a user could receive the token of another user

Security-critical Race Conditions

Of course, the bug we identified in this example is not really security critical, but similar, security critical examples are easily imaginable. For instance, assume that instead of a count variable, a security token for, e.g., session tracking is generated. If a switch happens between generating a token and sending it to the user, a user my receive the token of another user, which gives him access with the identity of the other user:

- Token A for user A is created and stored in an instance variable
- Thread switch
- Token B for user B is created, which overwrites the token in the instance variable
- User B receives Token B
- Thread switch
- User A also receives Token A

Use Instance Variables only when necessary

Using instance variables only when necessary helps reducing race conditions problems, because only instance variables are shared among threads. With the count-Variable, we have to use an instance variable because we want to keep rack of the total number of hits. But with the access token example described above, it's pointless (and actually totally wrong) to store it in an instance variable because there's no need to store it in the object across method calls. Therefore, using a local variable in the doGet-Method would solve the problem.

Example: Java Servlet (4)

- The easiest "fix" would be to avoid the problem at all, i.e. not using an instance variable
  - Because only instance variables are shared among threads
  - But here, this is not an option as we count the number of calls of the doGet-Method, so we must use an instance variable
- To fix of a race condition we must make sure that the made assumptions for correct behavior are indeed valid
  - Servlet example: make sure no thread switch can take place between updating the count variable and reading its new value
- First naïve attempt: write the two lines in one line

```
p.println(++count + " hits so far!");
```

- This most likely won't change anything
  - In Java bytecode, this still results in several instructions and the thread switch may take place between any two instructions

Example: Java Servlet (5)

- To truly solve the problem, we must make sure the relevant code section is atomic
  - Atomic means the code section executes as if the operations were a single unit in the sense that "no other thread can get between" during program execution
- To make multiple operations atomic, locking mechanisms are usually used
  - In Java, this can be achieved by using the per-object lock with the `synchronized` keyword
  - The synchronized keyword guarantees that at any time and with multiple threads accessing an object, at most one thread can be in any code section that is protected by the synchronized keyword

Example: Java Servlet (6)

- Second attempt: protect the method with synchronized

```
public class Counter extends HttpServlet {
  private int count = 0;

  public synchronized void doGet(HttpServletRequest in,
                   HttpServletResponse out)
                   throws ServletException, IOException {
    out.setContentType("text/plain");
    Printwriter p = out.getWriter();
    count++;
    p.println(count + " hits so far!");
  }
}
```

- This works, but is not as efficient as it could be
  - In particular, including the writing to the network into the critical section means that any blocked writing operation blocks the application

Example: Java Servlet (7)

- Third attempt: keep the synchronized section as small as possible

```
public class Counter extends HttpServlet {
  private int count = 0;

  public void doGet(HttpServletRequest in,
                    HttpServletResponse out)
                    throws ServletException, IOException {
    int myCount;
    out.setContentType("text/plain");
    Printwriter p = out.getWriter();
    synchronized(this) {
      mycount = ++count;
    }
    p.println(my_count + " hits so far!");
  }
}
```


Instance Variable vs. Local Variable

Note that unlike the instance variable count, my_count is a local variable to the doGet method and therefore not shared among threads using the object.

TOCTOU – Time-of-Check, Time-of-Use

- Race conditions not only occur in multithreaded programs, but in general when different processes on a system share resources
- This is where file-based race conditions come into play, which are most prominent among security-critical race conditions
- Most security-critical file-based race conditions follow this pattern:
  - There's a check of a file property that precedes the use of the file
    - E.g. it is checked whether a user is allowed to read a file
  - When using the file, it is assumed that the previous check was in indeed done on the current file → this is the assumption that must be valid
    - It is assumed that if the result of the previous check was positive, the user is indeed allowed to read the file that is used
  - If an attacker manages to invalidate this assumption, he can access files he shouldn't be allowed to access
    - Such defects are called time-of-check, time-of-use (TOCTOU) bugs

Example: Checking File Access Rights (1)

- The following code is part of a program that allows writing to files
  - The program runs setuid root, so the program has access to any file (so the effective user ID (EUID) of the process is root)
  - Therefore, the program checks if the user running the program (real UID, or simply UID) has access to a particular file before granting access

```
if(!access(file, W_OK)) {  /* checks if the user has write
                              access to file (pathname),
                              returns 0 on success */
  f = fopen(file, "w+");   /* open the file for writing */
  write_to_file(f);
} else {
  fprintf(stderr, "Permission denied when trying to \
                   open %s.\n", file);
}
```

- This sounds reasonable... but unfortunately, the program contains a major security vulnerability – can you spot it?

access

The access() function checks the file named by the pathname in the first argument for accessibility according to the access right in the second argument. It uses the real user ID in place of the effective user ID and the real group ID in place of the effective group ID.

The access function is defined by the POSIX.1 standard (unistd.h), the base of the Single Unix Specification, and should therefore be available in any conforming (or quasi-conforming) operating system/compiler (all official versions of Unix, including Mac OS X, Linux, etc.).

For a description, see: *http://www.opengroup.org/onlinepubs/009695399/functions/access.html*

Example: Checking File Access Rights (2)

- An attacker that has local access to the system (legitimate or not) can exploit the vulnerability to get write access to any file
  - The idea is that the attacker switches the files between checking and opening it
  - This can best be done using symbolic links
- The attacker's strategy is as follows
  - In his home directory, he creates a file and sets a symbolic link to it

```
$ touch dummy
$ ln -s dummy pointer
```

  - Now the attacker starts the program to write to **`pointer`**
  - Just between the check of the access rights and the opening of the file, the attacker changes the link, which gives him access to a file he shouldn't be able to access based on his rights

```
$ rm pointer;
$ ln -s /etc/shadow pointer
```

Example: Checking File Access Rights (3)

- Of course, executing these commands manually (redirecting the link) most likely won't be successful
- One therefore automates such attacks by writing a small program that
  - Sets the link (`pointer`) to a file the attacker is allowed to access (`dummy`)
  - Starts the program to write the file (`pointer`)
  - Redirects the link to the desired file (`/etc/shadow`)
  - Checks the desired file to see whether it was overwritten, e.g. by inspecting the modification date
  - Repeating the attack several times with minor timing variations will increase the probability that it will eventually be successful

Avoiding TOCTOU Problems

- Minimize the number of function calls that take a filename for an input
  - Use the filename only once for initial file access, which usually returns a file handle or a file descriptor for further access
    - This guarantees that as long the file handle is used, it is not possible for an attacker to exchange the underlying file by redirecting a symbolic link
  - In this example, first open the file and then use the returned file descriptor to check the access rights
- If possible, avoid doing your own access checking on files, leave that to the underlying operating system
  - E.g. by not running the program setuid root but with the rights of the user
    - But this is not always possible, e.g. server applications that are accessed over the network usually implement their own user management and access control
- In general, avoid running a program with high privileges (e.g. setuid root) unless absolutely necessary
  - If high privileges are needed think "especially hard" about security

Operating System File Access Control

This can usually only be used when local system users use local applications.

Final Exercise

- The following Java program allows listing the contents of a directory specified as command line parameter, by invoking a shell command using the java Runtime class
  - Imagine the code is part of a server application that allows listing the directory contents
  - Example: `java ListDirectoryContents .` lists the contents of the current directory
  - The program allows listing any directory, but should do nothing else
- Can you spot the (major) security-relevant bug? To which kingdom does it belong? How could it basically be fixed?

```
public class ListDirectoryContents {
  public static void main(String[] args) throws IOException {
    if(args.length != 1) {
      System.out.println("Specify the directory to list");
      System.exit(1);
    }
    Runtime runtime = Runtime.getRuntime();
    String[] cmd = new String[3];
    cmd[0] = "/bin/sh"; cmd[1] = "-c"; cmd[2] = "ls " + args[0];
    Process proc = runtime.exec(cmd);

    InputStream is = proc.getInputStream();
    InputStreamReader isr = new InputStreamReader(is);
    BufferedReader br = new BufferedReader(isr);
    String line;
    while ((line = br.readLine()) != null) {
      System.out.println(line);
    }
  }
}
```

The executed command is `/bin/sh -c ls args[0]` e.g. `/bin/sh -c ls .` and the output is displayed on stdout

Final Exercise – Solution

How to Start Reducing Coding Errors?

- There's a vast range of possible security-relevant mistakes one can do during the implementation of software
  - It's certainly overwhelming, especially for people that are just "entering" the field of secure software
- So what can you do to start reducing your number of coding errors?
  - Use a static code analysis tool (we will look at this later) → it will likely detect several of your bugs
  - During your projects, get "more security aware" and consult secure software guidelines for your language (C, Java, PHP, C#...) → there are many resources available (online & books)
    - E.g. the online documentation of the here used taxonomy of coding errors

Summary

- There's a wide spectrum of different types of security-relevant coding errors
- One way to classify them is according to Gary McGraws Taxonomy of Coding Errors
  - Uses 7 (+1) main classes of errors ("Kingdoms")
- Buffer overflows are a prominent type of bug and belong to the "Input Validation and Representation" kingdom
  - They happen if data is written beyond the end of an allocated buffer
- Using dangerous functions is a typical error of the "API Abuse" kingdom
  - In C, there exist safer versions for many string functions, such as **`strncpy`** instead of **`strcpy`** or **`fgets`** instead of **`gets`**
- A race condition is an error related to the "Time and State" kingdom
  - The typically happen in multithreaded programs or if multiple programs access shared resources (e.g. a file)