CS 453/698: Software and Systems Security

Module: An In-depth Study of Memory Errors

Lecture: Definition and exploits

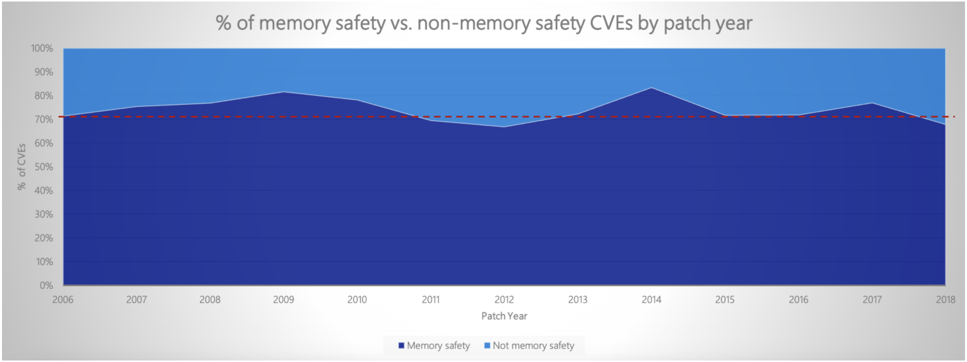
Meng Xu *(University of Waterloo)*

Winter 2025

Outline

1. Why study memory errors?
2. Demonstration of memory error exploits
3. A relatively formal definition of memory errors
4. Case study: Heartbleed vulnerability

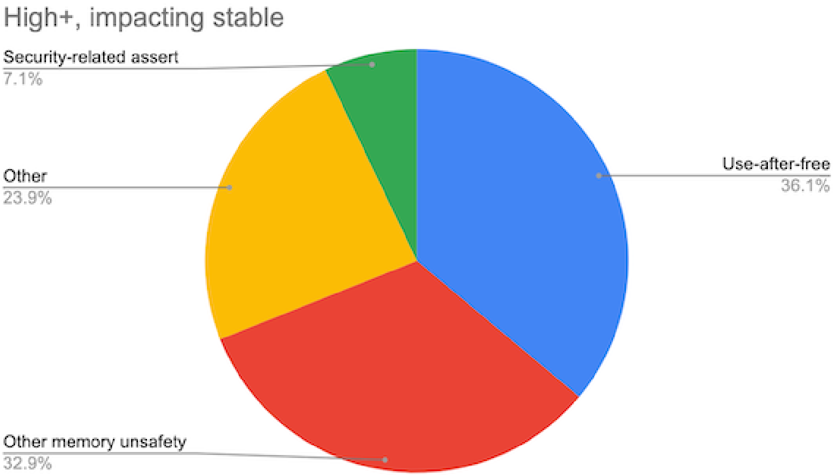
Memory errors are prevalent



Source: BlackHat IL 2019 talk by Matt Miller from Microsoft

Around 70% of all the vulnerabilities in Microsoft products addressed through a security update each year (2006 - 2018) are memory safety issues

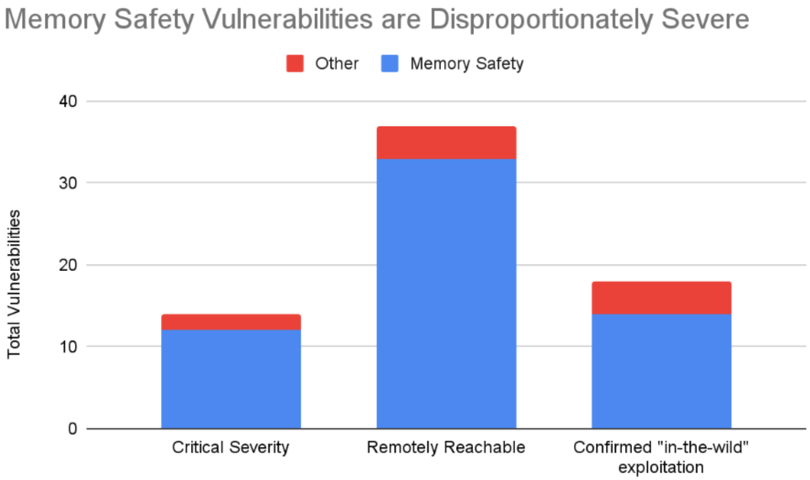
Memory errors are prevalent



Source: Chromium Memory Safety Report from Google.

Analysis based on 912 high or critical severity security bugs in Chromium reported in 2015 - 2020

Memory errors are prevalent



Source: Blog post Memory Safe Languages in Android 13 from Google.

Memory safety vulnerabilities disproportionately represent Android's most severe vulnerabilities

Memory errors can lead to severe consequences

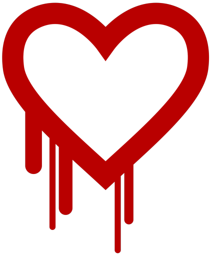
Heartbleed Vulnerability
(CVE-2014-0610)

Memory errors can lead to severe consequences

Heartbleed Vulnerability
(CVE-2014-0610)

- A security bug in version 1.0.1 of OpenSSL, which is a widely used implementation of the Transport Layer Security (TLS) protocol
- It was introduced into OpenSSL in 2012 and publicly disclosed in April 2014
- At the time of disclosure, some 17% (around half a million) of the Internet's secure web servers certified by trusted authorities were believed to be vulnerable to the attack

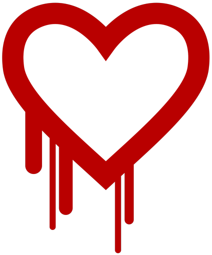
Memory errors can lead to severe consequences



Heartbleed Vulnerability (CVE-2014-0610)

- The Canada Revenue Agency (CRA) reported a theft of social insurance numbers belonging to 900 taxpayers, and said that they were accessed through an exploit of the bug during a 6-hour period on 8 April 2014.
- After the discovery of the attack, the agency shut down its website and extended the taxpayer filing deadline from 30 April to 5 May.

Memory errors can lead to severe consequences



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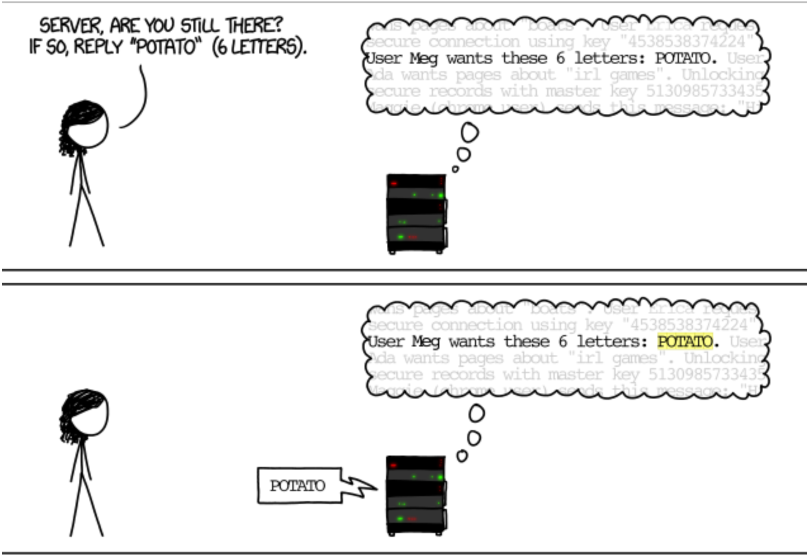
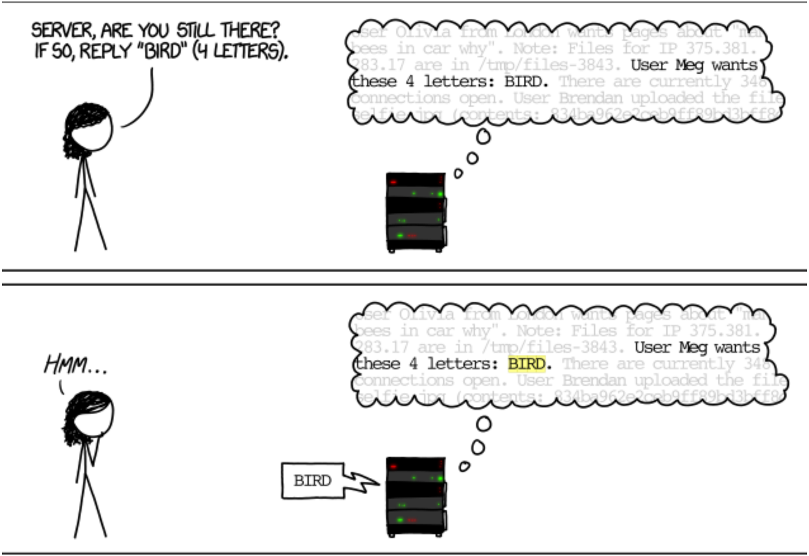
- After the discovery of the attack, the agency shut down its website and extended the taxpayer filing deadline from 30 April to 5 May.
- On 16 April, the RCMP announced they had charged a computer science student in relation to the theft with unauthorized use of a computer and mischief in relation to data.

Heartbleed explanation



Source: https://imgs.xkcd.com/comics/heartbleed_explanation.png

Heartbleed explanation



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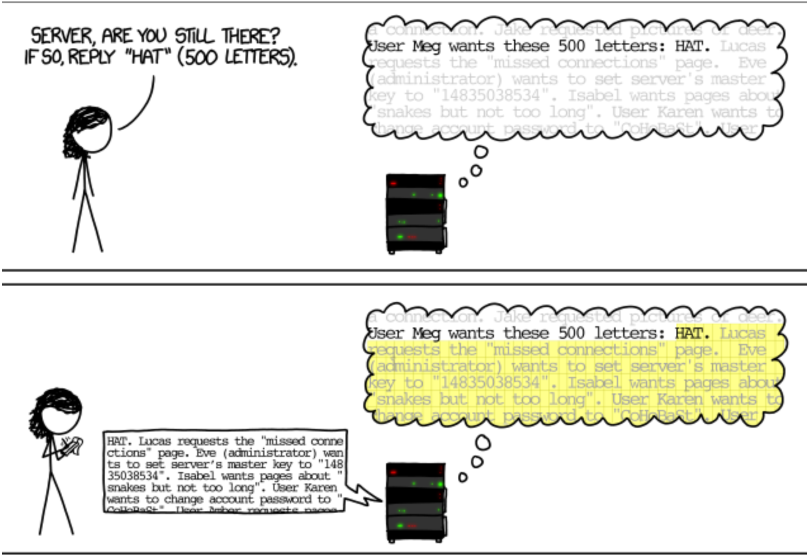

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Outline

Exploitation of a stack overflow

Demo

Stack layout (Linux x86-64 convention)

```c
long foo(
    long a, long b, long c,
    long d, long e, long f,
    long g, long h)
{
    long xx = a * b * c;
    long yy = d + e + f;
    long zz = bar(xx, yy, g + h);
    return zz + 20;
}
```

High address	
RBP + 24	h
RBP + 16	g
RBP + 8	return address
RBP	saved rbp
RBP - 8	xx
RBP - 16	yy
RBP - 24	zz
Low address	

Argument a to f passed by registers.

Exploitation of a use-after-free

Demo

Heap: what happens after `malloc()`?

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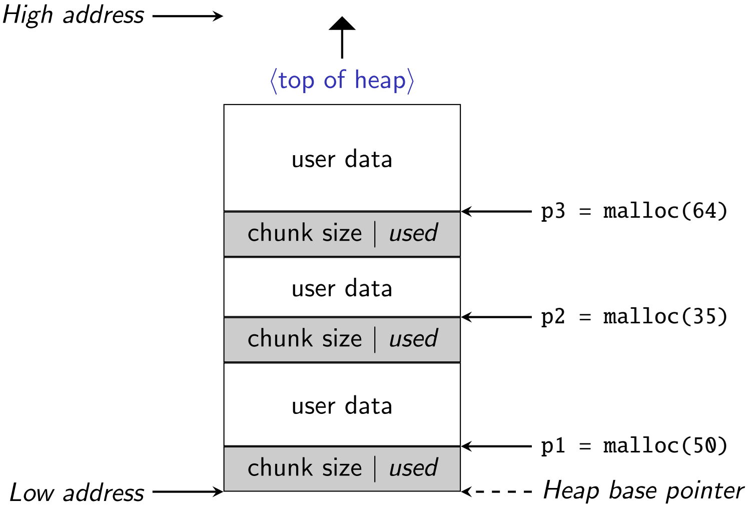
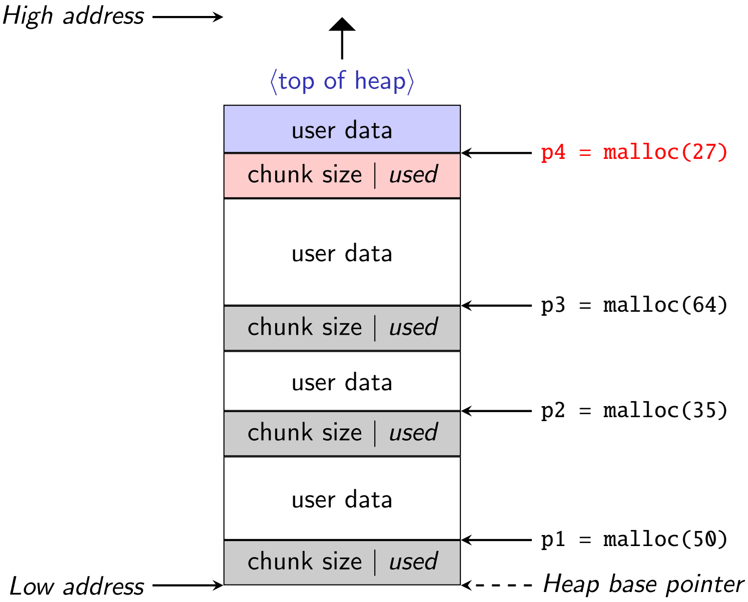
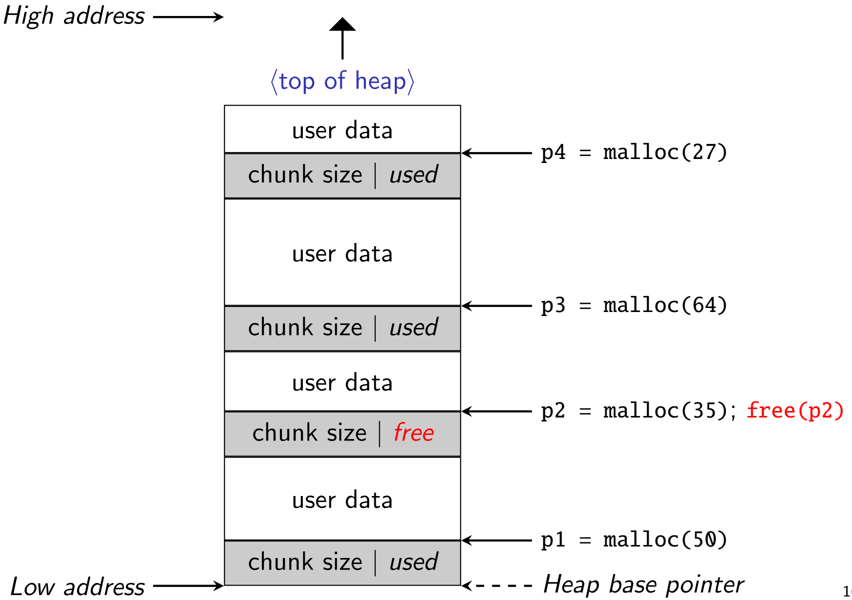


Heap: what happens after `malloc()`?



Heap: what happens after `free()`?

Heap: what happens after `free()`?



Real-world heap manager

For implementation details of the `glibc`[1] memory allocator, refer to the article from Azeria Labs.

[1]GNU C library

For exploitation of memory errors

Smashing The Stack For Fun And Profit

How2Heap — Educational Heap Exploitation

Bonus: memory layout

Q: What about stacks and heap in multi-threaded programs?

Bonus: memory layout

Q: What about stacks and heap in multi-threaded programs?

A: Stack and heap are treated different in multi-threading:

- each thread has its own stack
- all threads in the same process share the heap and global data

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A quick recap

This presentation is about memory corruption, a.k.a.,

- memory errors, or
- violations of memory safety properties, or
- unsafe programs

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- memory errors, or
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- unsafe programs

A program is memory safe if it is free of memory errors.

Definition: safety

Q: What is “safe” in memory safety?

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Observation 1: At runtime, memory is a pool of objects

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Observation 3: Once allocated, the size of an object never changes

Observation 4: A memory access is always object-oriented, i.e.

- Memory read: `(object_id, offset, length)`
- Memory write: `(object_id, offset, length, value)`

Definition: safety

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Wait..., in C/C++, pointers are just 32/64-bit integers. I can do: `int *p = 0xdeadbeef; int v = *p;` Which object do I refer to here?

Definition: safety

Q: What is "safety" in memory safety?

At any point of time during the program execution,
for any object in memory, we know its
`(object_id, size [int], alive [bool])`

At the same time, for each memory access, we know:

- Memory read: `(object_id, offset [int], length [int])`
- Memory write: `(object_id, offset [int], length [int], _)`

Definition: spatial safety

At any point of time during the program execution, for any object in memory, we know its
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- Memory read: `(object_id, offset [int], length [int])`
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It is a violation of spatial safety if:

- `offset + length >= size` or
- `offset < 0`

Example: spatial safety violations

```
int foo(int x) {
    int arr[16] = {0};
    return arr[x];
}
```

Example: spatial safety violations

```c
int foo(int x) {
    int arr[16] = {0};
    return arr[x];
}
```

```c
long foo() {
    int a = 0;
    return *(long *)(&a);
}
```

Definition: NULL-pointer dereference

```c
int foo(int *p) {
    // it is possible that p == NULL
    return *p + 42;
}
```

Definition: NULL-pointer dereference

```c
int foo(int *p) {
    // it is possible that p == NULL
    return *p + 42;
}
```

NULL-pointer dereference is sometimes considered as undefined behavior — meaning, its behavior is not given in the C language specification, although most operating systems chooses to panic the program on such behavior.

Definition: NULL-pointer dereference

At any point of time during the program execution,
for any object in memory, we know its
(**object_id** $\neq$ **0**, size [int], alive [bool])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)

Definition: NULL-pointer dereference

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- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)

It is a NULL-pointer dereference if

- `object_id == 0`

Definition: temporal safety

At any point of time during the program execution, for any object in memory, we know its
(**object_id**, size [int], alive [bool])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

Definition: temporal safety

At any point of time during the program execution, for any object in memory, we know its
`(`**`object_id`**`, size [int], alive [bool])`

At the same time, for each memory access, we know:

- Memory read: `(`**`object_id`**`, offset [int], length [int])`
- Memory write: `(`**`object_id`**`, offset [int], length [int], _)`
- Memory free: `(`**`object_id`**`)`

It is a violation of temporal safety if:

- `!alive`

Example: temporal safety violations

```
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    return *p;
}
```

Example: temporal safety violations

```
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    return *p;
}
```

```
int *ptr;

void foo() {
    int p = 100;
    ptr = &p;
}
int bar() {
    return *ptr;
}
```

Example: temporal safety violations

```c
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    return *p;
}
```

```c
int *ptr;

void foo() {
    int p = 100;
    ptr = &p;
}
int bar() {
    return *ptr;
}
```

```c
int foo() {
    int *p = malloc(sizeof(int));
    *p = 42;
    free(p);
    free(p);
    return *p;
}
```

Definition: temporal safety (revisited)

At any point of time during the program execution,
for any object in memory, we know its
(**object_id**, size [int], status [alloc|init|dead])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

Definition: temporal safety (revisited)

At any point of time during the program execution,
for any object in memory, we know its
`(object_id, size [int], status [alloc|init|dead])`

At the same time, for each memory access, we know:

- Memory read: `(object_id, offset [int], length [int])`
- Memory write: `(object_id, offset [int], length [int], _)`
- Memory free: `(object_id)`

It is a violation of temporal safety if:

- Read: `status != init`
- Write: `status == dead`
- Free: `status == dead`

Example: temporal safety violations

```c
int foo() {
    int p;
    return p;
    // what is the value returned?
}
```

Example: temporal safety violations

```c
int foo() {
    int p;
    return p;
    // what is the value returned?
}
```

```c
int foo() {
    int *p = malloc(sizeof(int));
    return *p;
    // what is the value returned?
}
```

Definition: memory leak

At any point of time during the program execution,
for any object in memory, we know its
`(`**`object_id`**`, size [int], status [alloc|init|dead])`

At the same time, for each memory access, we know:

- Memory read: `(`**`object_id`**`, offset [int], length [int])`
- Memory write: `(`**`object_id`**`, offset [int], length [int], _)`
- Memory free: `(`**`object_id`**`)`

Definition: memory leak

At any point of time during the program execution,
for any object in memory, we know its
(**object_id**, size [int], status [alloc|init|dead])

At the same time, for each memory access, we know:

- Memory read: (**object_id**, offset [int], length [int])
- Memory write: (**object_id**, offset [int], length [int], _)
- Memory free: (**object_id**)

It is a memory leak if exists one **object_id** whose:

- status != dead

Example: memory leak

```c
int foo() {
    int *p = malloc(sizeof(int));
    int *q = malloc(sizeof(int));
    *p = 42;
    free(q);
    return *p;
}
```

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Heartbleed vulnerability I

```
int dtls1_process_heartbeat(SSL *s) {
  unsigned char *p = &s->s3->rrec.data[0], *pl;
  unsigned short hbtype;
  unsigned int payload;
  unsigned int padding = 16; /* Use minimum padding */

  /* Read type and payload length first */
  hbtype = *p++;
  n2s(p, payload);
  pl = p;

  /* ... redacted ... */

  if (hbtype == TLS1_HB_REQUEST) {
    unsigned char *buffer, *bp;

    /* Allocate memory for the response */
    buffer = OPENSSL_malloc(1 + 2 + payload + padding);
    bp = buffer;

    /* Enter response type, length and copy payload */
    *bp++ = TLS1_HB_RESPONSE;
```

Heartbleed vulnerability II

```
        s2n(payload, bp);
        memcpy(bp, pl, payload);

        /* Random padding */
        RAND_pseudo_bytes(bp, padding);

        /* Send out the response */
        r = dtls1_write_bytes(
            s, TLS1_RT_HEARTBEAT, buffer, 3 + payload + padding
        );

        /* ... redacted ... */

        /* Clean-up used resources */
        OPENSSL_free(buffer);
        return r;
    }

    else { /* ... redacted ... */ }
}
```

Patch for the Heartbleed vulnerability I

```
diff --git a/ssl/d1_both.c b/ssl/d1_both.c
index 7a5596a6b3..2e8cf681ed 100644
@@ -1459,26 +1459,36 @@ dtls1_process_heartbeat(SSL *s)
    unsigned int payload;
    unsigned int padding = 16; /* Use minimum padding */

-   /* Read type and payload length first */
-   hbtype = *p++;
-   n2s(p, payload);
-   pl = p;
-
    if (s->msg_callback)
        s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
            &s->s3->rrec.data[0], s->s3->rrec.length,
            s, s->msg_callback_arg);

+   /* Read type and payload length first */
+   if (1 + 2 + 16 > s->s3->rrec.length)
+       return 0; /* silently discard */
+   hbtype = *p++;
+   n2s(p, payload);
+
```

Patch for the Heartbleed vulnerability II

```diff
+   if (1 + 2 + payload + 16 > s->s3->rrec.length)
+       return 0; /* silently discard per RFC 6520 sec. 4 */
+   pl = p;
+
    if (hbtype == TLS1_HB_REQUEST)
        {
        unsigned char *buffer, *bp;
+       unsigned int write_length = 1 /* heartbeat type */ +
+                               2 /* heartbeat length */ + payload + padding;
        int r;

+       if (write_length > SSL3_RT_MAX_PLAIN_LENGTH)
+           return 0;
+
        /* Allocate memory for the response, size is 1 byte
         * message type, plus 2 bytes payload length, plus
         * payload, plus padding
         */
-       buffer = OPENSSL_malloc(1 + 2 + payload + padding);
+       buffer = OPENSSL_malloc(write_length);
        bp = buffer;
```

$\langle$ **End** $\rangle$