Low level security

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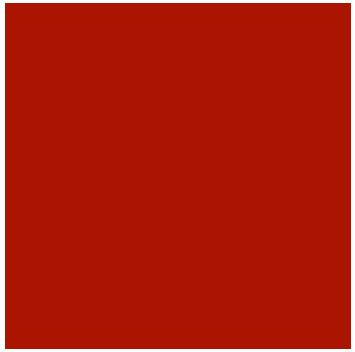
What's going on

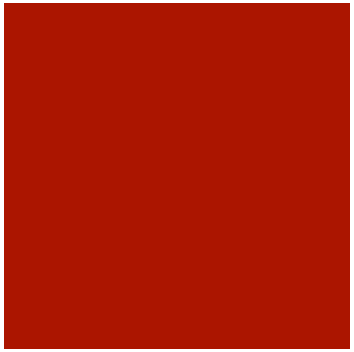
- Stuff is getting hacked all the time
- We're writing tons of software
  - Often with little regard to reliability let alone security
- The regulatory environment is pretty open
  - Due to our failures as technologists this might change

Why low level specifically?



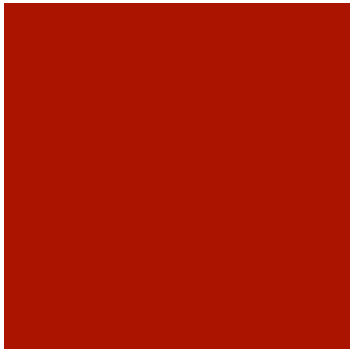
- Programs written in C have two unfortunate intersecting properties
  - They do something important, servers, cryptography, etc.
  - By construction they permit subtle low level memory errors that allow for malicious attackers to completely compromise systems

How subtle are we talking?



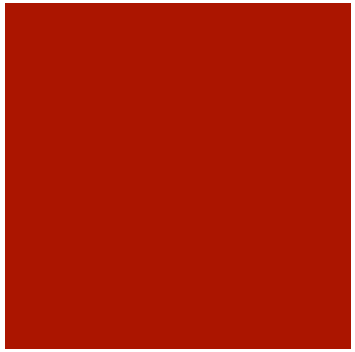
- Heartbleed was undiscovered for two years
- Many bugs are found in released products even after internal pen testing and review

What is memory safety?



- A good question that started 2 days of discussion in the PL group
  - So probably no coherent answer yet
- Generally, memory safety assures *spatial* and *temporal* safety
  - Do not use memory after it is released
  - Do not write outside the bounds of an object

Could there be other errors?



- `goto fail` was not memory safety
- Some SSL CNAME checking errors were not memory safety
- Character conversion and "fail open" logic can still cause big problems
- Let's just look at what we can find with tools for memory safety and correctness

What is clang-analyzer?

- A symbolic execution framework for C/C ++ built in clang
- Operates on the clang AST
- clang-analyzer is actually separate from the LLVM project proper
- A core symbolic execution framework that drives state through compilation units

Extensible checkers

- A modular checker architecture where checkers “visit” state and
  - Do nothing
  - Create new state
  - Report a bug

Symbolic state

- The symbolic execution system keeps a symbolic state for every path it executes through a program
- This state serves two purposes
  - Checkers can query state to identify bugs
  - When a bug is identified, the state is unrolled and projected onto the source code

Extensible symbolic state

- Values stored in symbolic state are also extensible
- Checkers can define new types of values to store in the state

Example output

```
1464        n2s(p, payload);
1465        pl = p;
1466
1467        if (s->msg_callback)
```

1 Taking false branch →

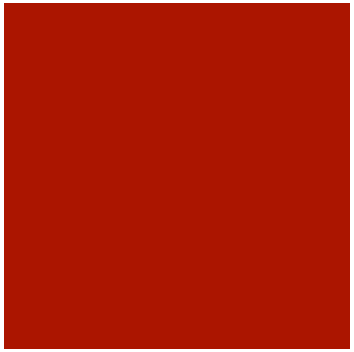
```
1468                s->msg_callback(0, s->version, TLS1_RT_HEARTBEAT,
1469                        &s->s3->rrec.data[0], s->s3->rrec.length,
1470                        s, s->msg_callback_arg);
1471
1472        if (hbtype == TLS1_HB_REQUEST)
```

2 ← Assuming 'hbtype' is equal to 1 →

3 ← Taking true branch →

```
1473                {
1474                unsigned char *buffer, *bp;
1475                int r;
1476
```

Symbolic Execution



- Program testing technique
- Evaluate a program with symbolic variables instead of concrete variables
- Consider all branches and conditions that “might be” within a program

Example

```
int nonneg(int a) {
  if(a >= 0) {
    return a;
  } else {
    return 0;
  }
}
```

How does a computer explore what this code does?

What if we could evaluate this program with every possible input?

Uses of symbolic execution

- This technique sits at the heart of modern flaw finding systems
- How could we use it as a tool?

What could we check?

- At each point in the program a checker visits, it has access to the current state
- Values are symbolic, symbolic integer values include range
- Some checkers that currently exist:
  - Array bounds
  - `malloc` size parameter overflow
  - Imbalanced mutex usage

Heartbleed

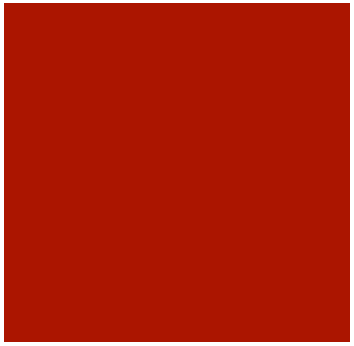
- Epic OpenSSL vulnerability that allowed for (somewhat) arbitrary read of heap data
- Ultimate cause – read object out of bounds
- Difficult to detect statically
- Could we write a checker to find it? How?

The bug

```
int
tls1_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);
  p += 2;
        pl = p;
```

The bug



```
buffer = OPENSSL_malloc(1 + 2 + payload + padding);
bp = buffer;

/* Enter response type, length and copy payload */
*bp++ = TLS1_HB_RESPONSE;
s2n(payload, bp);
memcpy(bp, pl, payload);
```

Impact

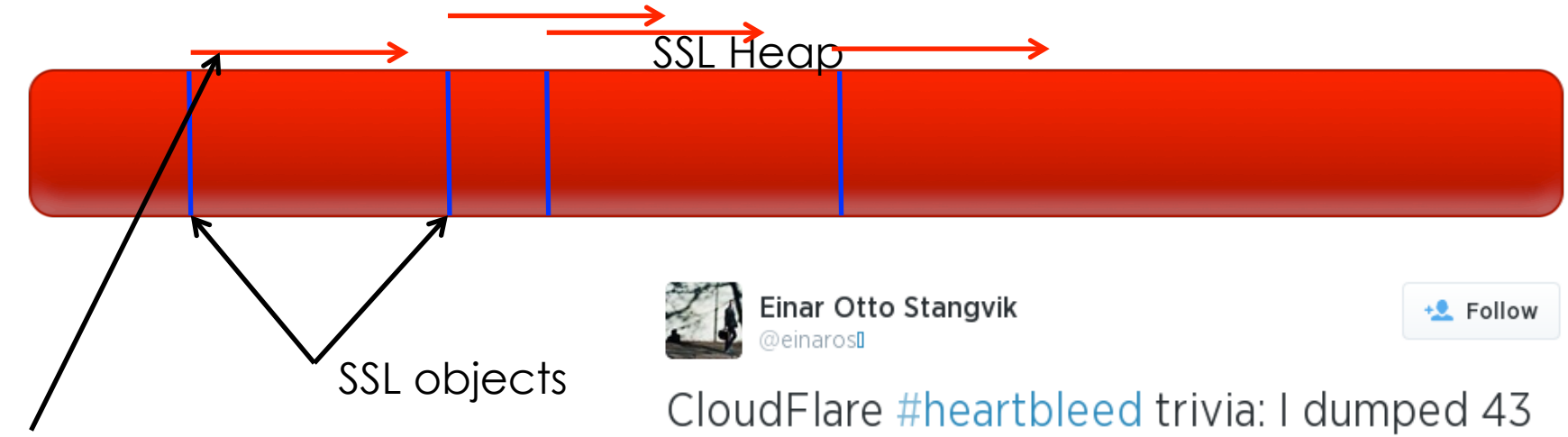
- Read a specific amount of memory from the OpenSSL heap and send it to the client
  - Client is unauthenticated
  - Deliciously, the exfiltrated data sent to the attacker is encrypted
    - NIDS is useless, though you can see heartbeat messages with long sizes

Impact

- Deliciously, as long as the `memcpy` doesn't produce a segmentation fault, this isn't an observable attack in any sytsems security model
  - HIDS and SELinux is useless

How bad could this get?

- One `SSL` object allocated per connection
- Read values could include self or near-self referencing pointer values
- By establishing concurrent connections, could snapshot entire heap state



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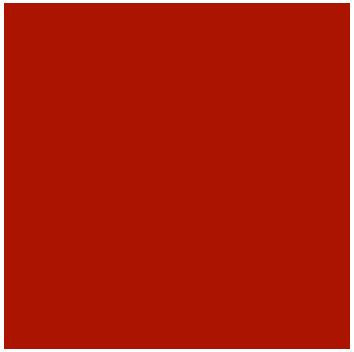
Follow

CloudFlare #heartbleed trivia: I dumped 43 GB of data, using 700k packets. One RSA prime is found 194 times. 0.02% prime to heartbeat ratio.

How could we find it statically?

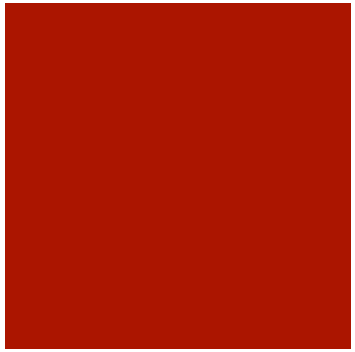


- Need to know that `payload` variable is fully attacker controlled
- Use `ntohl` as an annotation that a variable is attacker controlled
- Identify unconstrained uses of those variables

What about the web?

- I want to live in a world with widespread verified code
- At the moment it is probably an easier sell to say that our medical and avionic systems should be formally verified
  - You mean they're not right now?
  - Well, some of them are in Europe
- We can apply these same techniques to find bugs in web applications though

What are pragmatic things?



- There are some software security focused classes to take
  - Mike Hicks is teaching one in the fall on Coursera
- There are companies that will do you a good job on pen testing your stuff
- There are ways you can write and design your applications to make failure less certain

Programming Tips

- One way to view pointers is as *capabilities**
  - A pointer is a language resource
- Every use of a pointer should be performed with concern to safety invariants
  - Ownership
  - Bounds
  - Lifetime

* http://www.pl-enthusiast.net/2014/07/21/memory-safety/

Ownership

- Which *thread of execution* is interacting with the pointer?
- Multiple threads interacting with shared memory is a source of both security and correctness errors
- Ownership questions usually resolved with a *mutex*

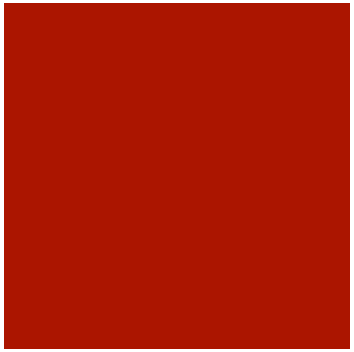
Bounds

- Is the access with the pointer *in bounds*
- Is the data being read/written within the bounds of the specified field or object?
- Bounds can sometimes be enforced via type checking
- For arbitrary buffers, carry around a size field and check the size before use

Lifetime

- Has an allocated pointer *fallen out of lifetime*, or **died**
- Using dead pointers is uncouth
  - Could result in writing into a now-live region of memory, resulting in *use after free*
- Control the lifetime of pointers with *reference counting*

Checking tools



- clang-analyzer is a static analyzer
- Dynamic analyzers can find bugs with fewer false positives and time spent
- Traces concrete execution of a program
- Examines the trace for violations of memory safety

Checking tools

- AddressSanitizer
  - Component of clang compiler
  - Emits code with checks embedded
- valgrind
  - Stand-alone checker, works on unmodified binaries
  - Executes code and checks for safety violations

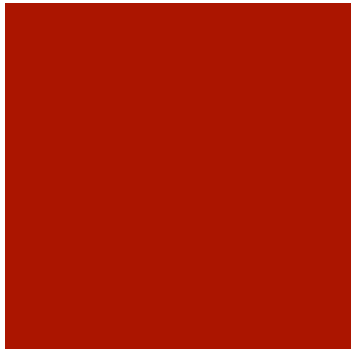
Find Heartbleed with ASAN

- Fuzzer would need to produce heartbeat packets
- ASAN instruments reads and writes
- At runtime, the act of reading out of bounds triggers a fault

Avoid the snake

- Of course you should ask yourself, why am I writing in an unmanaged language?
- I think that Java and C# are on the front line of winning our war with memory safety
- So what could we do in the future and what is the frontier for making new programs better?

Types and memory safety?



- In some sense we already tolerate advanced static analysis of our programs before we let them run
  - We just call it "type checking"
- How much information about a programs behavior can we put into the type system?
  - Could we encode a state machine into the type system?

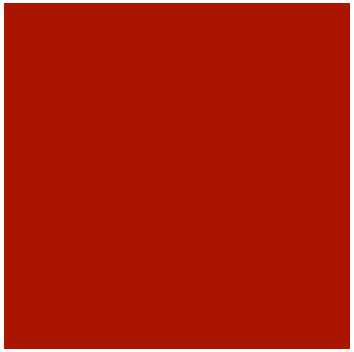
Neat type applications

- Session types
  - Essentially put state machine transitions into types
- Refinement types
  - Put logical constraints on the use of types
  - "Practical" implementations in LiquidHaskell, F7
- Check "high level" properties
  - Does "login" actually do the right thing?

We still have C though

- We **can** bolt a lot of checking onto C code though
- frama-c
  - Open source analysis framework
  - ACSL – specification language for behavior
- Write C code with low and high level guarantees

frama-c success stories

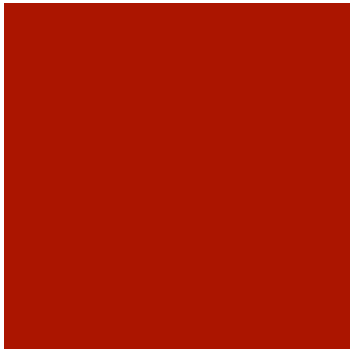


- Formally verified PolarSSL implementation
- After-the-fact retrofit of memory safety guarantees onto older C codebase
  - Helped by PolarSSL modularity
- Could we do better?

Compartmentalization

- ocaml-tls implements the TLS protocol in OCaml
- They use native code bindings to implement block ciphers
  - There are some reasons you want to do this like timing channels and performance
  - The code is small enough that you could formally verify it for memory safety

Well specified formats

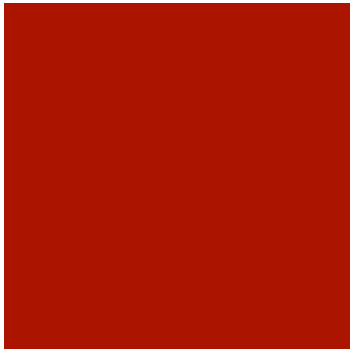


- When sending or receiving rich data, let other coders worry about serialization and deserialization
- Encode messages into protocol buffers, CapnProto, thrift, etc.

Well encapsulated libraries

- If your crypto library abstraction wants to make you choose a cipher suite and decide if you want HMAC or not, you have a bad library
- If your product depends on maintaining some kind of security invariant, consider hiring a security adult

Conclusion



- It's scary
- We have a lot of low level code
- We don't know what it does
- We're getting better
- Please don't write more of it