Hacking in C

The C programming language

Radboud University, Nijmegen, The Netherlands

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- Many "interesting" security issues

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- You can switch `gcc` to other C standards using, e.g., `-std=c89`
- Use `-pedantic` flag to issue warnings if your code doesn't conform to the standard

C vs. C++

- C is the basis for C++, Objective-C, and many other languages
- C is **not a subset of C++**, e.g.,

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- Use compiler by the same vendor to compile
- Lets you use, e.g., highly optimized C libraries
- Common scenario:
  - Write high-speed code in C (and assembly)
  - Write so-called wrappers around this for easy access in C++

A "portable assembler"

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"If programming languages were…"

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- … countries
  https://www.quora.com/
  If-programming-languages-were-countries-which-country-would-each-language-
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- . . . boats
  http://compsci.ca/blog/if-a-programming-language-was-a-boat/

“If programming languages were. . . ”

“C is a nuclear submarine. The instructions are probably in a foreign language, but all of the hardware itself is optimized for performance.

Syntax and semantics

Syntax of a programming language

- Spelling and grammar rules
- Defines the language of **valid programs**
- Syntax errors are caught by the compiler
- Classical example: forget a `;` at the end of a line

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Semantics of a programming language

- Defines the **meaning** of a valid program
- In many languages semantics are fully specified
- Runtime errors (exceptions) are part of the semantics
- C is **not** fully specified!

Unspecified behavior

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  - Number of bits in one byte
- Fairly hard to write fully specified C programs
- For this course: if not otherwise stated assume `gcc` (version 6.x, 7.x, or 8.x) compiling for AMD64.

Undefined behavior

- Different from unspecified behavior: **undefined behavior**
- Program reaches a state in which it may do **anything**
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- It is totally acceptable for a program to delete all your data when running into undefined behavior
- Sometimes we can *make* a program do this (or something similar)
- Most attacks in the course: exploit undefined behavior

C compilation

- Four steps involved in compilation, can stop at any of those
- First step: Run the preprocessor (`gcc -E`)
  - Include code from `#include` directives
  - Expand macros from `#define` directives
  - Expand compile-time (static) conditionals `#if`
  - The C preprocessor is almost Turing complete
  - See `https://github.com/orangeduck/CPP_COMPLETE` for a Brainfuck interpreter written in the C preprocessor

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  - Generates so-called **object files**
- Fourth step: Linking (simply run `gcc`, this is default)
  - Put object files together to a binary
  - Linker errors include missing functions or function duplicates
  - Also include external libraries here (e.g., `-lm`)
  - Caution: order of arguments can matter!

Memory abstraction 1: where data is stored

- Programmers typically don't know where data is stored
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- Sometimes important: always read the variable from memory
- C has keyword `volatile` to enforce this
- Disables certain optimization

Where is data allocated?

- C has the `&` operator that returns the address of a variable
- Example:
  - Let's say we have a variable `int x = 12`
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- Much more on pointers later, for the moment let's print them:

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- The "inverse" of & is `*`, i.e., `*(&x)` gives the value of `x`

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- ... and then I write in assembly and avoid the compiler alltogether
- Problem with `register`: no guarantee that the value isn’t spilled
- Requesting the address of a `register` variable is invalid!

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- For this course: a byte consists of 8 bits

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- (Most) registers have the size of machine words
- Often loads and stores are more efficient when **aligned** to a word boundary
- von Neumann architecture: also programs are just bytes in memory
- Only difference between data and program: what you do with it

`char`

- Most basic data type: `char`
- From the C11 standard:

  "An object declared as type char is large enough to store any member of the basic execution character set."
- More useful definition: a `char` is a byte, i.e., the smallest addressable unit of memory
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- It's `a` and `c`, because `'2'` has ASCII value 50.

Another quick question...

- What does the following code do?:

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for(i=42;i>=0;i--)
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}
```

Another quick question. . .

- What does the following code do?:

```
char i;
for(i=42;i>=0;i--)
{
  printf("Crypto stands for cryptography\n");
}
```

- Answer: it depends (and it really does!)
- C standard does not define whether `char` is signed or unsigned
- Make explicit by using `signed char` or `unsigned char`

Other integral types

- C11 provides 4 more integral types (each signed and unsigned):
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  - `int`: typically 4 (but sometimes 2) bytes
  - `long`: typically 4 or 8 bytes
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- Integral constants can be written in
  - Decimal, e.g., 255
  - Hexadecimal, using `0x`, e.g., `0xff`
  - Octal, using `0`, e.g., `0377`

Floating-point and complex values

- C also defines 3 "real" types:
  - `float`: usually 32-bit IEEE 754 "single-precision" floats
  - `double`: usually 64-bit IEEE 754 "double-precision" floats
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- Small example:

```
double a; /* assume IEEE 754 standard */
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a += 6755399441055744;
a -= 6755399441055744;
```

- What does this code do to a?

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- What does this code do to `a`?
- Answer: it rounds `a` according to the currently set rounding mode

Printing values

Have already seen various examples of **format strings**, let's summarize:

```
printf("%d", a); /* prints signed integers in decimal */
printf("%u", b); /* prints unsigned integers in decimal */
printf("%x", c); /* prints integers in hexadecimal */
printf("%o", c); /* prints integers in octal */
printf("%lu", d); /* prints long unsigned integer in decimal */
printf("%llu", d); /* prints long long unsigned integer in decimal */
printf("%p", &d); /* prints pointers (in hexadecimal) */
printf("%f", e); /* prints single-precision floats */
printf("%lf", e); /* prints double-precision floats */
printf("%llf", e); /* prints extended-precision floats */
```

There's quite a few more, but these get you fairly far.

stdint.h

- Often we need to know how large an integer is
- Example: crypto primitives are optimized to work on, e.g., 32-bit words
- Solution: Fixed-size integer types defined in `stdint.h`
  - `uint8_t` is an 8-bit unsigned integer
  - `int8_t` is an 8-bit signed integer
  - `uint16_t` is a 16-bit unsigned integer
  - ...
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- `printf("%llu\n", a);` for `uint64_t a` may produce warnings
- Solution: `printf("%" PRIu64 "\n", a)`
- For signed values, e.g., `PRId64`
- Printing in hexadecimal: `PRIx64`

Implicit type conversion

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- Example:

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float pi, r, circ;
pi = 3.14159265;
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- Often these rules are perfectly intuitive:
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- Often these rules are perfectly intuitive:
  - Convert "less precise" type to more precise type, preserve values
  - Compute modulo 2^{16}, when casting from `uint32_t` to `uint16_t`
- However, these rules can be rather counterintuitive:

```
unsigned int a = 1;
int b = -1;
if(b < a) printf("all good\n");
else printf("WTF?\n");
```

Explicit casts

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- Careful, this does not generally work (undefined behavior ahead)!

A small quiz

What do you think this program will print?

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unsigned char x = 128;
signed char y = x;
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(Obviously, the answer is “unspecified behavior” – it’s C after all)

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- Can use the same hardware for signed and unsigned addition

Endianess

- Let's consider the 32-bit integer $287454020 =$0x11223344
- How would you put it into memory. . . ,like this?:

```
|    11    |    22    |    33    |    44    |

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- A quick poll: What do you find more intuitive?

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```

- Or would you rather have this?

```
|    a3    |    a2    |    a1    |    a0    |

  0x0...0    0x0...1   0x0...2   0x0...3
```

- Again a quick poll: What do you find more intuitive?

Endianess, the conclusion

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- Examples for big-endian CPUs:
  - PowerPC
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- ARM can switch endianess (is "bi-endian")
- The problem with little-endian intuition is just that we write left-to-right (but use Arabic numbers)