Introduction to Reverse Engineering

REVERSE ENGINEERING

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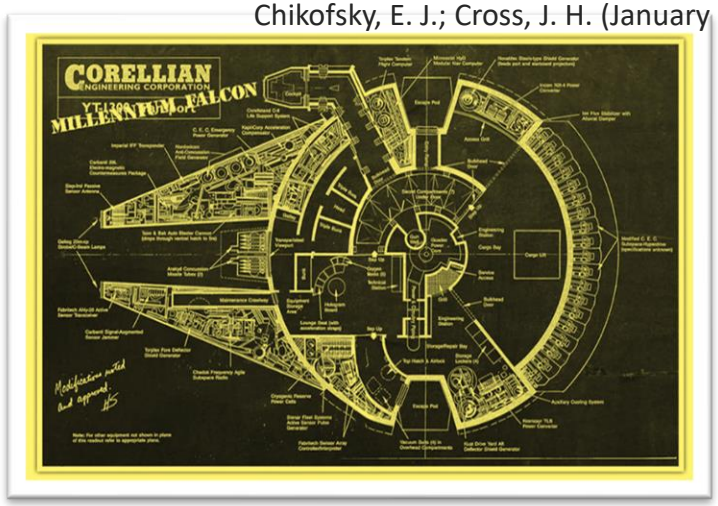
What is Reverse Engineering (RE)

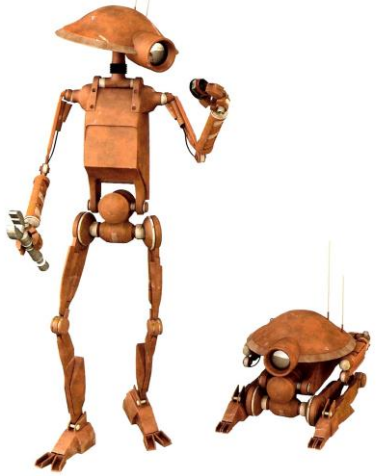
- Reverse Engineering (RE) is the process of extracting features from any man-made artifact (Engineered)
  - Knowledge
  - Design blueprints
  - Function
- It’s not purely scientific research: with RE the artifact was engineered
  - The scientific process doesn’t generically focus on a product
    - Focus is on mechanisms, processes, events, phenomena
    - … and we have no idea whether the universe was engineered or not ☺

What is Reverse Engineering (RE)

The process of **analyzing** a **subject system** to **identify** the system's **components** and their **interrelationships** and to **create representations** of the system in another form or at a higher level of abstraction

Chikofsky, E. J.; Cross, J. H. (January 1990). "Reverse engineering and design recovery: A taxonomy" (PDF). IEEE Software. 7: 13–17. doi:10.1109/52.43044





Forward Engineering

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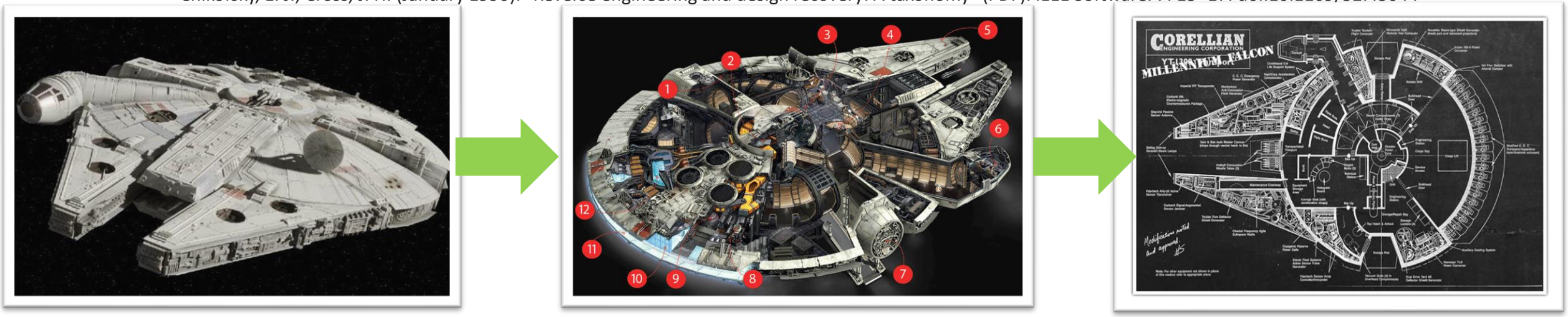

Reverse Engineering

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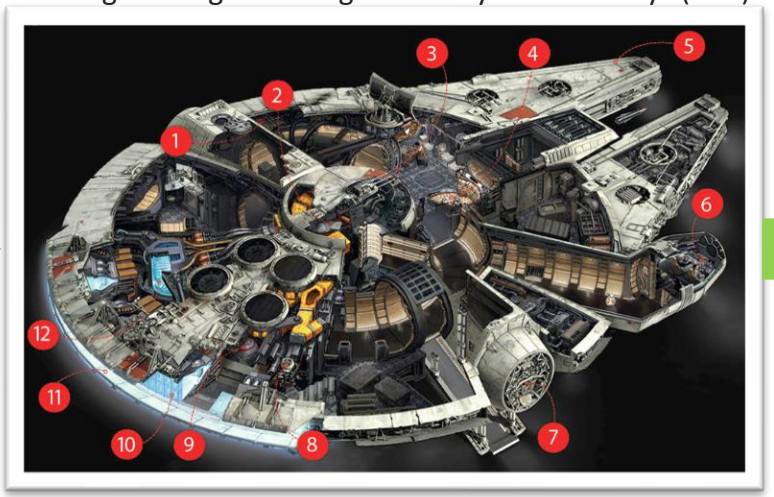

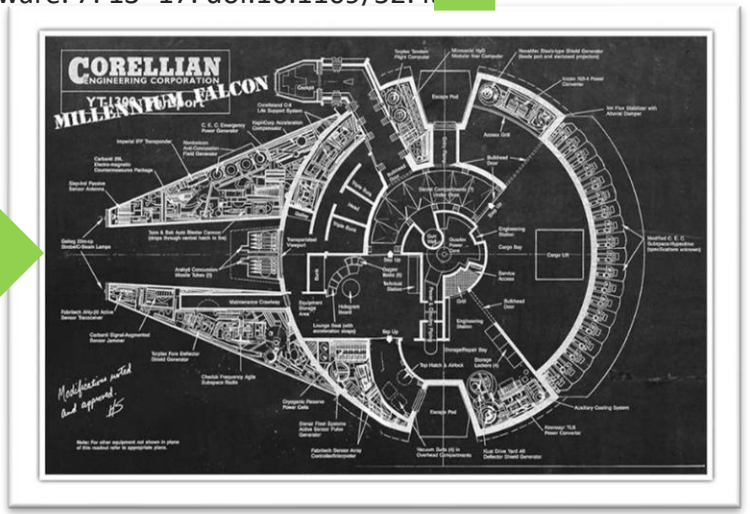

Reverse Engineering

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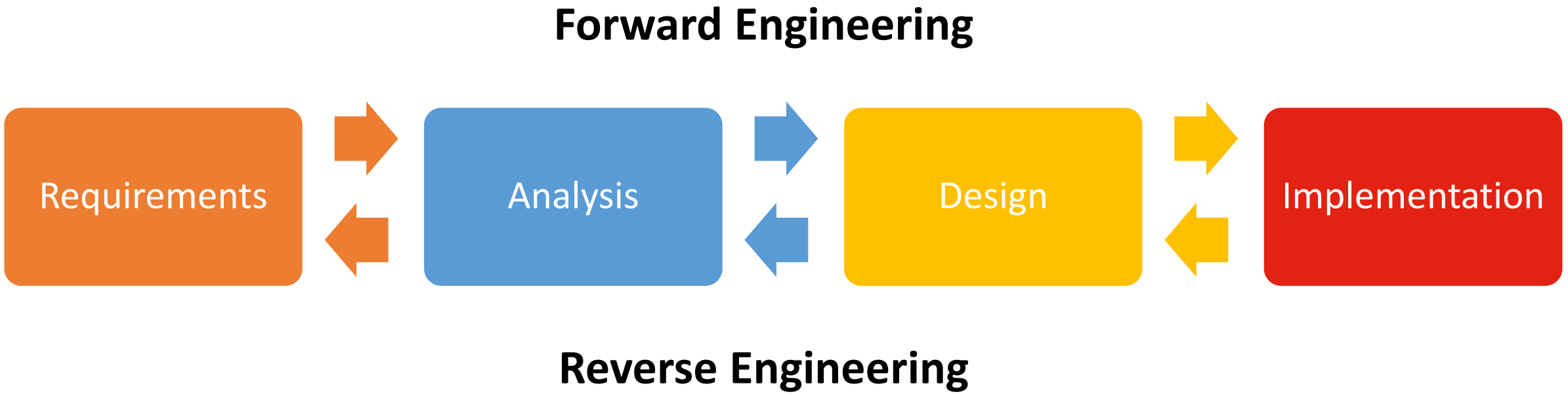
What is Reverse Engineering (RE)



- Processes are not perfect, in either direction.
- Implementation may not fully comply with requirements, while reversed engineered analysis may not fully represent the implementation design, and design will be limited

RE Concepts

- **Abstraction Level**
  - The result of a RE process will produce a design at a given abstraction level.
  - The higher the better
- **Completeness**
  - Level of detail at the abstraction level.
  - The greater the better
- **Interactivity**
  - How much humans are required for RE.
  - The lesser the better (higher automation)

When do we have RE activities?

- RE **always evolved with engineering** and existed since its dawn
  - It is frequently done informally by everyone in their daily lives
- Every time **we look at a software/device/system** and try to understand how it works, or understand any aspect of its behavior and structure
  - Because we want to make a better one
  - Because we wish to estimate if it suits a purpose…
- Every time we **look at our code** and try to find what it was supposed to do
  - Especially when there is no documentation

Why RE is Relevant and Required

Personal Education

- Observing a product allows anyone to learn from its characteristics.
  - Why it behaves that way
  - What it does
  - How it does something
  - Why something doesn't happen

- One can **complement engineering** education by observing code/products made by others
  - Open-source software plays an important role here
    - Because it the source is available, it doesn't mean that structure, components, etc… are readily available or understood
  - Actually… instead of learning from patterns, **why not learn from its application as implemented by other professionals**?
    - There are a lot of "hidden" subtleties due to the experience of their authors

Why RE is Relevant and Required

Work around limitations

- Products are engineered in order to **provide some value**, and **turn profit**
  - Some value = value perceived by the buyers, in relation to other products
  - Profit = max price for the minimal cost
- Products are frequently built to promote further revenue
  - Support contracts, build an ecosystem, help sell other products
  - Closed in their interfaces and limited in their feature set
- Reverse engineering can be used **to increase the feature set**
  - After the product is made, and without cooperation from manufacturer

Why RE is Relevant and Required

Work around limitations

Magic Lantern extends existing Cameras with a huge amount of extra features

https://magiclantern.fm/

3D scanning vehicles enables aftermarket variants to produce alternative parts

https://www.creaform3d.com/

Observing existing parts allows new parts to be designed to improve reliability, performance, design..

Why RE is Relevant and Required

Make a product compatible

- A product is developed for a set of scenarios. **What if we want it to operate on another, unexpected, environment?**

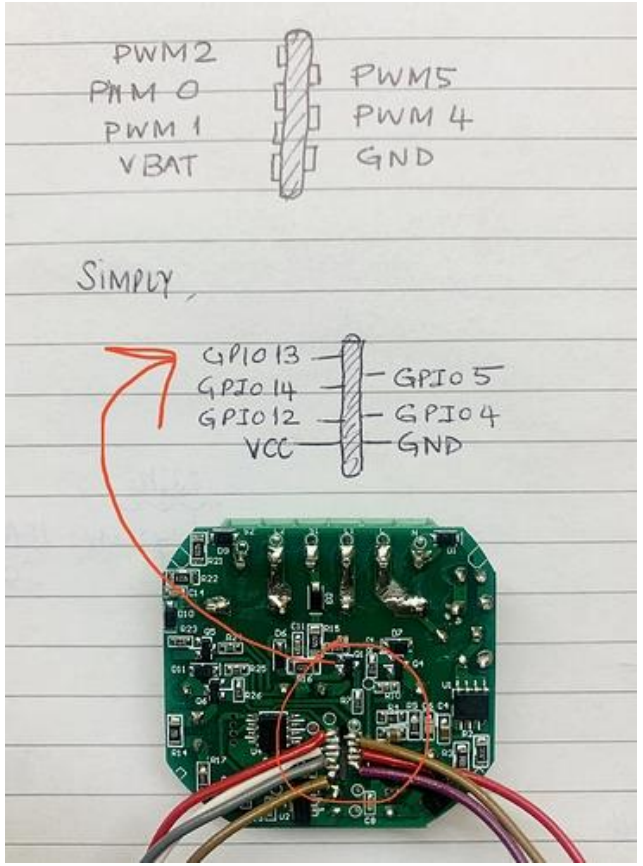
- RE allows obtaining **relevant design/operation information**
  - To modify the product to fit the new environment
    - Some components may be reconstructed
  - To build adapters integrating the product

- In corporate world it's standard to have products adapted to a specific use case
  - Process takes a long time, and is expensive
  - RE may provide a simpler route
  - Especially relevant if the manufacturer doesn't provide that service
    - Or simply doesn't exist

Why RE is Relevant and Required

Make a product compatible

- Make/DIY movements are keen on RE
- Driven by integrating and enhancement
  - Mostly for personal use
  - Community driven
- Frequently without cooperation from manufacturers
  - Alarms: [ParadoxAlarmInterface/pai]
  - Sports bracelets: [Gadgetbridge]
- Sometimes with some collaboration
  - [Magic Lantern]



Unkown tuya chip - Hardware - Home Assistant Community (home-assistant.io)

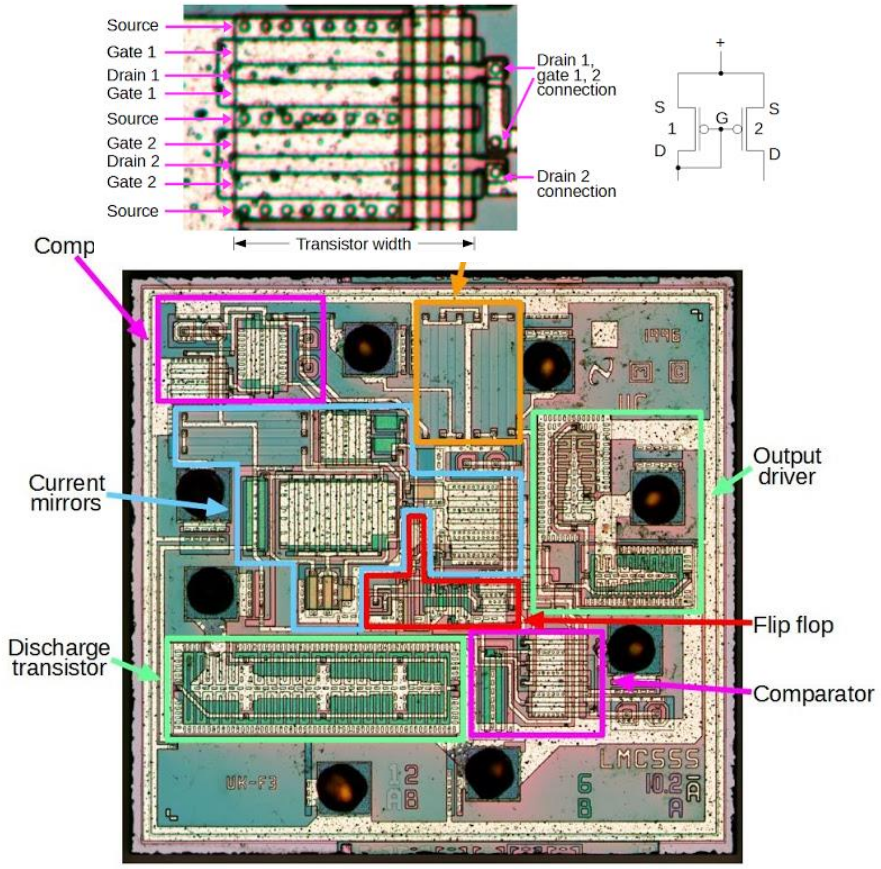
Why RE is Relevant and Required

Learn from other's products or from products of other domains

- Companies must determine the values/weaknesses of products in competing markets
  - What strategies/materials/methods/technology are used by competitors
  - Helps segmenting market and setting prices
  - Helps acquiring knowledge to develop new product
- Also: does a certain product violates a patent of ours?
  - Includes patented designs
- RE can be used for that purpose
  - and can feed information to engineering
  - determine the need for judicial actions protecting Intellectual Property

Why RE is Relevant and Required

Learn from other's products or from products of other domains



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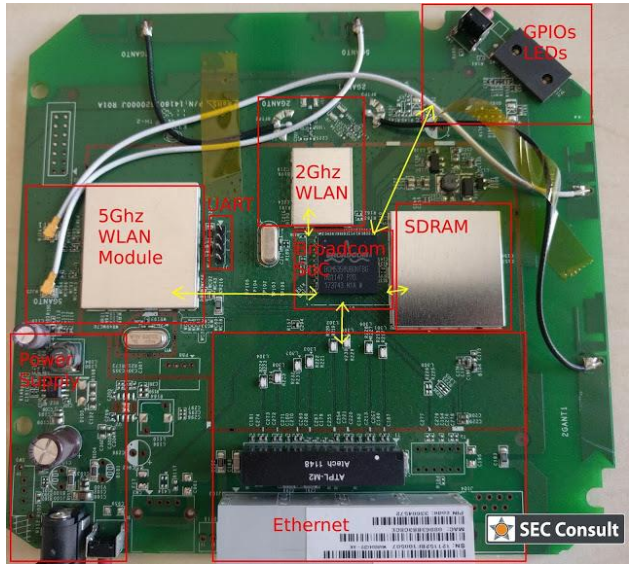
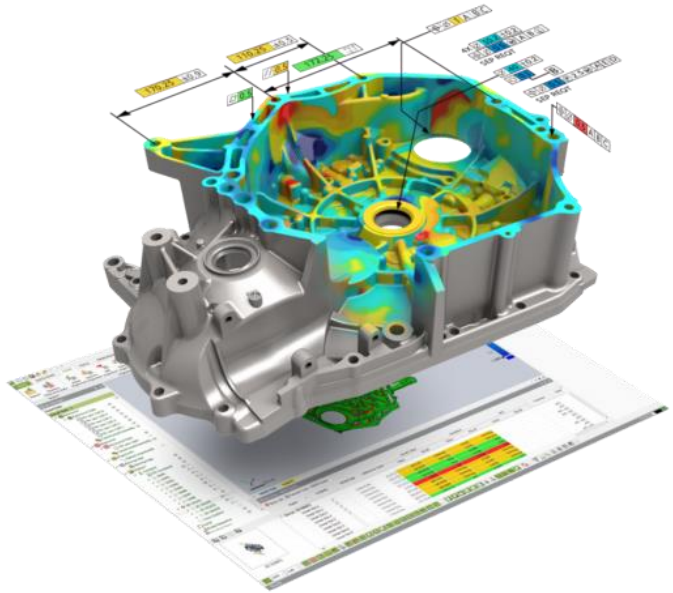


https://sec-consult.com/



https://dewyseng.com/

Why RE is Relevant and Required

Finding the purpose of a certain code/binary blob or part

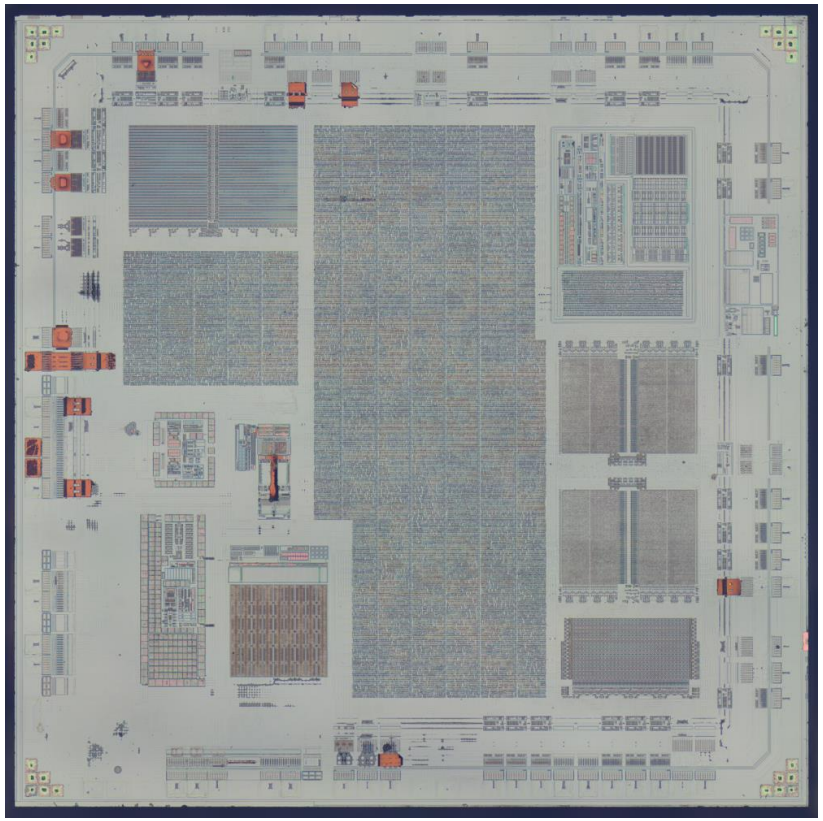
- Engineers frequently assume that an engineered entity is known (They trust dependencies)
  - That is… if you develop something, you know what it does
  - Also assume (or wish) that documentation exists

- What if:
  - documentation is lost?
  - the blob is external to the company?
  - the blob is misbehaving?
  - the blob was modified?
  - the engineer/supplier is not trusted?
  - the part is fake?
  - the company needs to validate the design process?

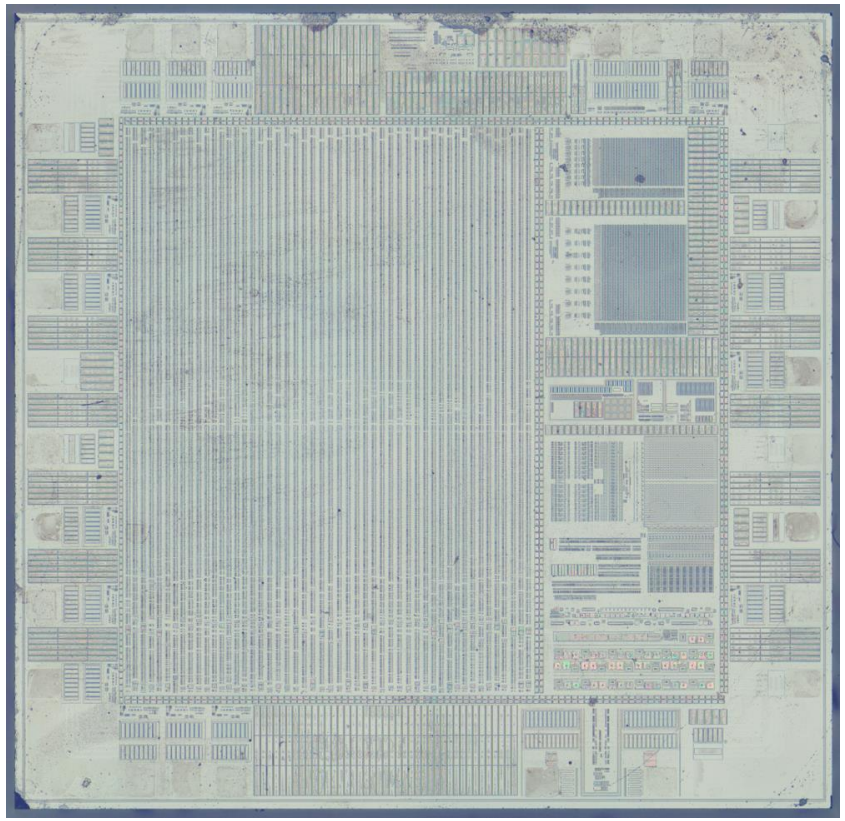
- RE can recover a similar design from the implementation, independently of the documentation, or the original design

Why RE is Relevant and Required

Finding the purpose of a certain code/binary blob or part



Fake FT232RL



Genuine FT232RL

https://zeptobars.com/en/read/FTDI-FT232RL-real-vs-fake-supereal

Why RE is Relevant and Required

Discovering flaws and faults

- Implementation may deviate from design
  - … it always deviates
- Implementation may present flaws due to unseen aspects
  - Processes used
  - Technology used
  - Interaction with additional components
  - Manufacturing flaws
  - Knowledge and experience
- RE is used in the scope of software testing to validate systems
  - Symbolic execution and Fuzzy testing are ways of helping the reverse engineering
  - Characterize if a given implementation reproduces the expected design
  - Identify additional modes

Why RE is Relevant and Required

Find and analyze malicious code

- For Anti-Virus, and Malware researchers, source code is not available
  - Or for offensive/red teams in black box scenarios

- **Malware detection relies on reverse engineering** to understand programs
  - RE allows the identification of patterns of malicious code
  - May rely on:
    - Interaction patterns
    - Bytecode structure
    - Communication with external hosts
    - Binary structure
    - Text contents
    - …

- Some RE is done in real time to find unknown malware
  - Or at least to identify suspect code, triggering further inspection

Limitations

- May be illegal in some cases, or lead to ambiguous situations
  - Higher risk of jeopardizing products developed
- Requires trained and experienced staff
  - Which is not abundant
- It’s costly in terms of time, resources and money
  - Expensive tools, scarce number of researchers, lengthy process
- May lead to incomplete or incorrect designs.
  - No guaranteed result!
  - An RE activity may be a complete waste of resources (time, staff, money)

Legal Framework

- The legality of RE is not assured a priori
  - varies with jurisdiction
  - varies with what is being reversed
  - varies with the purpose of the RE activity
  - varies with the impact to the product owner
- Applicable legislation:
  - USA: Digital Millennium Copyright Act
  - EU: EU Directive 2009/24
- This only applies to third parties
  - Product owners are free to use their own products as they seem fit
  - RE for the purpose of Software Quality Control

Legal Framework

Allowed situations (Europe, Directive 2009/24/EC)

The unauthorized reproduction, **translation**, **adaptation** or **transformation** of the form of the code in which a copy of a computer program has been made available **constitutes an infringement of the exclusive rights of the author**.

- .. circumstances may exist when such a reproduction of the code and translation of its form are indispensable to obtain the necessary information **to achieve the interoperability of an independently created program with other programs**.

- .. in these limited circumstances only, performance of the acts of reproduction and translation by or on behalf of **a person having a right to use a copy of the program** is legitimate and compatible with fair practice…

Legal Framework

Allowed situations (Europe, Directive 2009/24/EC)

- Article 5 b): To learn

The person **having a right to use a copy of a computer program** shall be entitled, without the authorisation of the rightholder, to **observe, study or test the functioning** of the program **in order to determine the ideas and principles** which underlie any element of the program **if he does so while performing any of the acts** of loading, displaying, running, transmitting or storing the program **which he is entitled to do**.

- **Broad Interpretation**: if you own a legitimate copy of the software, and are able to load it/run it/etc… you may analyze it for the purpose of learning

Legal Framework

Allowed situations (Europe, Directive 2009/24/EC)

- Article 5 b): To learn

- Caveats:
  - Replicating an algorithm may not be allowed, as a copy of the work infringes the copyright
  - Copy protection mechanism cannot be overcome
    - If there is a copy protection and you cannot freely execute the program, you do not have authorization to use it
  - Methods for bypassing protections are not legal
    - Crackers, keygens

- EULAs cannot restrict RE tasks

Legal Framework

Allowed situations (Europe, Directive 2009/24/EC)

- Article 6: Decompilation is generally allowed for the purposes listed in this directive, but mostly focusing on interoperability

- (allowed when) indispensable to obtain the information necessary to achieve the interoperability of an independently created computer program with other programs

- Provided that the following conditions are met:
  - those acts are performed by the licensee or by another **person having a right to use a copy of a program**, or on their behalf by a person authorized to do so
  - the information necessary to achieve interoperability **has not previously been readily available** to the persons referred to in point (a); and
  - those **acts are confined** to the parts of the original program which are necessary in order to achieve interoperability.

Legal Framework

Allowed situations (USA, DMCA)

- **Interoperability**: even circumventing DRM
- **Encryption research**: if the protection prevents the evaluation of the technology
- **Security testing**: determine if a software is secure and to improve it
- **Regulation**: to limit what information is presented to minors
- **Government Investigation**: government agencies are not affected
- **Privacy protection**: users may reverse and circumvent data gathering technologies
- EULAs may restrict RE actions, although this is not guaranteed by law

Eldad Eilam, 2005

What RE Recovers?

- **System structure**: its components and their interrelationships, as expressed by their interfaces
- **Functionality**: what operations are performed on what components
- **Dynamic behavior**: system understanding about how input is transformed to output
- **Rationale**: design involves decision making between a number of alternatives at each design step
- **Construction**: modules, documentation, test suites, etc.

Chih-Wei Lu et al, “Reverse Engineering”, Handbook of Software Engineering and Knowledge Engineering, Vol.2

Software Reversing Levels

System Level Reversing

- Observe how the software is provided and how it operates
  - Involves analyzing the environment, packaging, dependencies, and then observed behavior
  - May require tools to intercept traffic, system calls, input/output

- End goal: collect information to direct further analysis
  - Important in order to select tools, processes, and overall strategy
    - Language use, packaging algorithms, encryption
  - Important to characterize behavior and identify external dependencies
    - Remote servers involved, files accessed, communication channels used

Software Reversing Process

Code Level Reversing

- Extract design concepts and algorithms from binaries
  - Compiled to binary code or bytecode.

- It’s a complex, architecture dependent process
  - Some say “an art form”
  - Expensive enough that competitive RE is not usually pursued
    - To fully reverse and reassemble a given competing software (except in some cases)

- Makes use of tools capable of representing the low-level language in something “human compatible”
  - Compiler optimization and obfuscation make this process uncertain
  - Perfect reconstruction is frequently impossible as low-level languages do not use the same constructs as higher-level ones

Software Reversing Activities

- Understanding the processes
  - Large scale observation of the program at a process level
  - Identification of major components and their functionality
- Understanding the Data
  - Understand data structures used
- Understanding Interfaces
  - Which interfaces exist and how the process reacts to them

Software Reversing

- Programs are developed in a high-level programming languages
  - C, C++, C#, Java, Python, Go…
- A compiler converts the high-level instructions to low level instructions
  - Machine Code: instructions that are executed directly by the CPU
  - Bytecode: instructions that are executed by a middleware, VM or Interpreter
- Reverse Engineering involves understanding low level instructions
  - Which is not easy and is costly
  - Requires knowledge of the specific target being analyzed (the VM, the CPU)
    - Different CPUs have different opcodes and execution behavior

Low level languages

Machine Code

- Each CPU has a specific instruction set
  - Associated to rules regarding structure, execution flow,

- When a program is compiled to “binary”, the high-level logic is converted to a sequence of instructions
  - This sequence may be executed by a family of CPUs or a single model
  - Running this sequence on another CPU may involve binary translation (conversion)

- Humans are typically not capable of reading binary instructions, but instructions are always able to be translated to Assembly
  - Good: We can read binary code
  - Bad: each CPU has a specific variant of Assembly. Also, assembly is not simple.

Low level language

Machine Code

```
// Original C
int square(int num) {
    return num * num;
}
```

```
//ARM64 GCC 5.4
square(int):
        sub     sp, sp, #16
        str     w0, [sp, 12]
        ldr     w1, [sp, 12]
        ldr     w0, [sp, 12]
        mul     w0, w1, w0
        add     sp, sp, 16
        ret
```

```
//MIPS64 GCC 5.4
square(int):
        daddiu  $sp,$sp,-32
        sd      $fp,24($sp)
        move    $fp,$sp
        move    $2,$4
        sll     $2,$2,0
        sw      $2,0($fp)
        lw      $3,0($fp)
        lw      $2,0($fp)
        mult    $3,$2
        mflo    $2
        move    $sp,$fp
        ld      $fp,24($sp)
        daddiu  $sp,$sp,32
        j       $31
        nop
```

Compiler Explorer (godbolt.org)

```
//PowerPC GCC 4.8.5
square(int):
        stwu     1,-32(1)
        stw     31,28(1)
        mr      31,1
        stw     3,8(31)
        lwz     10,8(31)
        lwz     9,8(31)
        mullw   9,10,9
        mr      3,9
        addi    11,31,32
        lwz     31,-4(11)
        mr      1,11
        blr
```

```
//x86_64 gcc 5.4
square(int):
        push    rbp
        mov     rbp, rsp
        mov     DWORD PTR [rbp-4], edi
        mov     eax, DWORD PTR [rbp-4]
        imul    eax, DWORD PTR [rbp-4]
        pop     rbp
        ret
```

Low level languages

Machine Code

- For compiled programs, the RE tasks involves extracting information from the sequence of Assembly instructions
  - Disassembly is automatic, the rest frequently it isn’t

- Reconstruction is never perfect!
  - Different level of abstraction: e.g., it is not trivial to recover C++ class structure and OOP relations from Assembly code
  - **Different compilers generate different assembly** for the same source code
  - **Same compiler may generate different assembly** for the same source code
    - Optimization flags, CPU matching, protection mechanisms, target object type…

Low level languages

Bytecode

- Some languages are compiled to a bytecode (!= machine code)
  - Intermediate language that is processed by a VM or framework
  - .NET, Java, Python, JS, LISP, LUA, Ocaml, Tcl, FoxPro, WebAssembly

- Bytecode contains a compact (optimized) representation of the higher layer structures
  - Framework/VM will execute bytecode in the target CPU
  - Same bytecode usually can be executed in multiple CPUs, provided there is a native VM implementation
    - The Java moto: Write Once, Run Anywhere

- Bytecode allows easier extraction of information, provided there is such route
  - May recover classes, function names, and even comments (but not always)
  - Traditional decompiling tools will not process bytecode (that easily)

Tools

System monitoring tools

- Allow observing application behavior as the application runs
  - To extract system level information
  - Know interfaces, and data files used, resource usage, communication methods

- Some relevant:
  - /proc/pid: kernel structures showing relevant information about a process
  - strace: logs system calls with their arguments
  - lsof: list open files (including folders, sockets, pipes…)
  - PyREBox: creates virtual environments to analyze an application running

Tools

System monitoring tools - strace

```
$ stract wget http://www.ua.pt

munmap(0x7fd09f21d000, 200704)          = 0
ioctl(0, TIOCGPGRP, [26769])            = 0
getpgrp()                               = 26769

write(2, "Connecting to www.ua.pt (www.ua."..., 59Connecting to www.ua.pt (www.ua.pt)|193.136.173.58|:443... ) = 59

socket(AF_INET, SOCK_STREAM, IPPROTO_IP) = 4
connect(4, {sa_family=AF_INET, sin_port=htons(443), sin_addr=inet_addr("193.136.173.58")}, 16) = 0
ioctl(0, TIOCGPGRP, [26769])            = 0
getpgrp()                               = 26769
write(2, "connected.\n", 11connected.
)            = 11
getrandom("\x30\x8d\x68\xe3\xfd\x69\x26\xfb\x02\xad\x85\xa4\x6d\x7d\x9d\x4a\x44\xae\xd5\x9f\xf2\xa6\xe9\x17\xc2\xbc\x48...
brk(0x55822c787000)                     = 0x55822c787000

sendmsg(4, {msg_name=NULL, msg_namelen=0,
msg_iov=[{iov_base="\26\3\1\2\0\1\0\1\374\3\3\352\245z\277e\243\274\342\257\232\351_\301\246C\271\302\257t\366\203"...,
recvfrom(4, "\26\3\3\0A", 5, 0, NULL, NULL) = 5
recvfrom(4, "\2\0\0=\3\3O\264\262\264x\256&\22\350\371\346\267Z\212\243\217\335\350\223\325\272H\344\0\356\230"...,
recvfrom(4, "\26\3\3\v\255", 5, 0, NULL, NULL) = 5
recvfrom(4, "\v\0\v\251\0\v\246\0\6\2410\202\6\2350\202\5\205\240\3\2\1\2\2\20\6\264\27\f\327\357\254"...,
recvfrom(4, "\26\3\3\1M", 5, 0, NULL, NULL) = 5
```

Tools

System monitoring tools - pyREBox

Tools

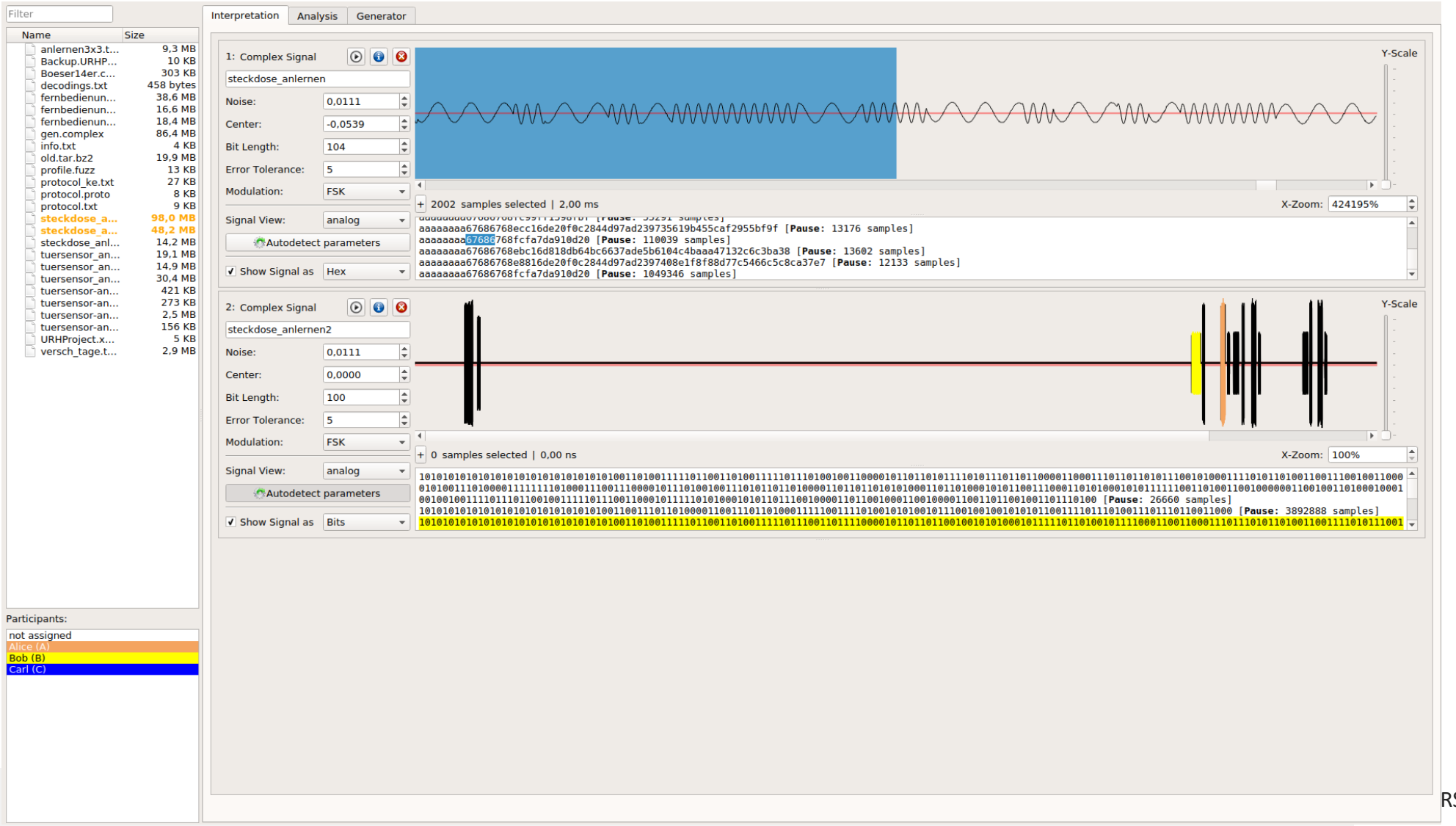
Communication monitoring tools

- Intercept or observe traffic exchanged with the process
  - May also filter or change data units

- Some relevant tools:
  - ZAP, mitmproxy: conduts MITM attacks to analyse interactions
  - wireshark: all purpose packet sniffer and powerful decoder
  - Logic Analysers: allow monitoring communication electronic communication buses
  - Automatic Protocol Reversers: extract structure from flows, sometimes supporting encrypted flow
    - For a comprehensive list: https://github.com/techge/PRE-list

Tools

Communication monitoring tools – Universal Radio Hacker



Tools

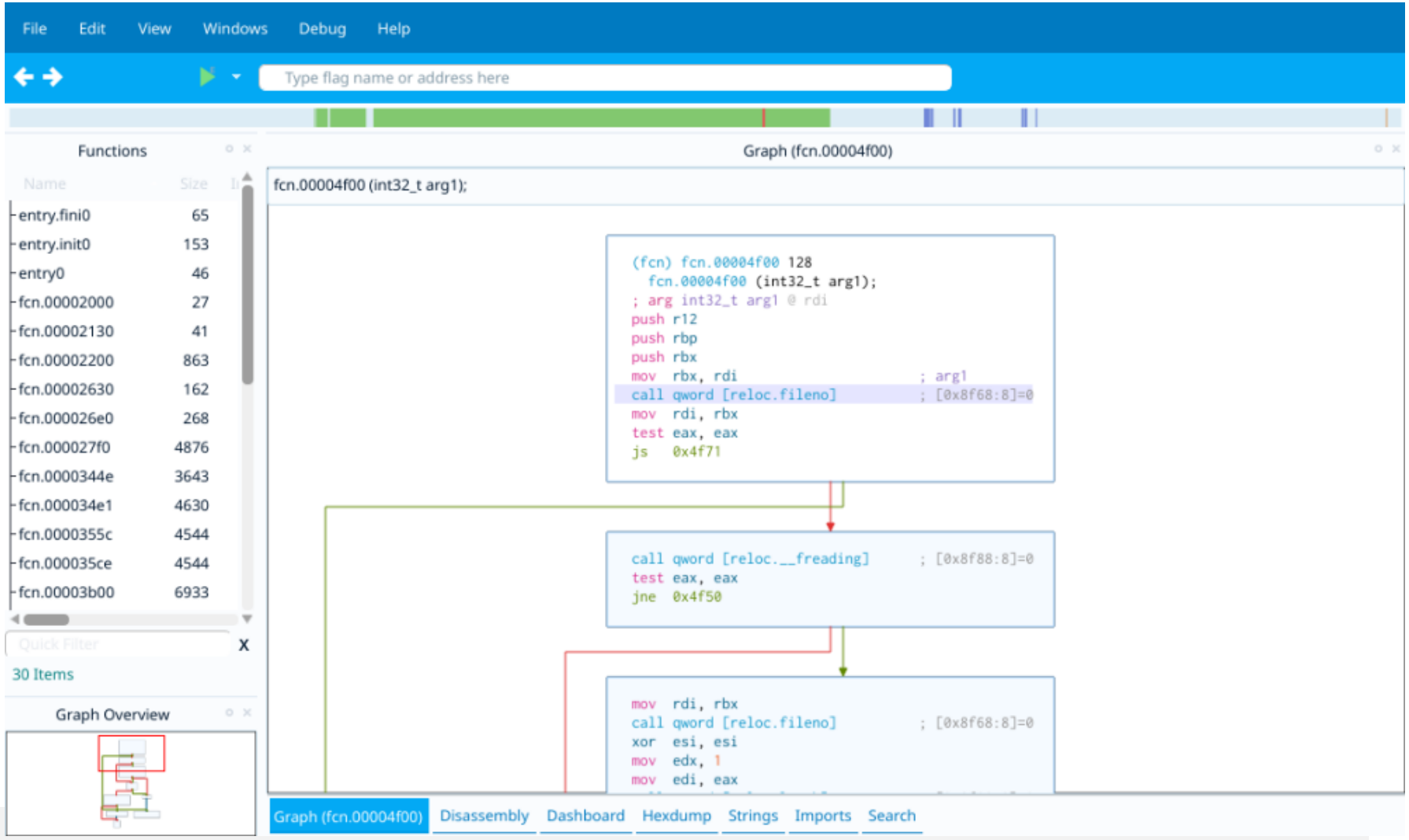
Disassemblers

- Convert bytecode or machine code into a higher layer language
  - Using static analysis
  - For machine code, this is Assembly
  - For bytecode, an intermediate language is presented (e.g., smali in Java)
  - May extract higher layer constructs
    - Data structures
    - Function prototypes
    - Function call charts

- Some relevant tools:
  - IDA Pro, Ghidra, Radare2, BinaryNinja, Hopper: general purpose, feature rich disassemblers

Tools

Disassemblers – Cutter (A frontend to radare2)

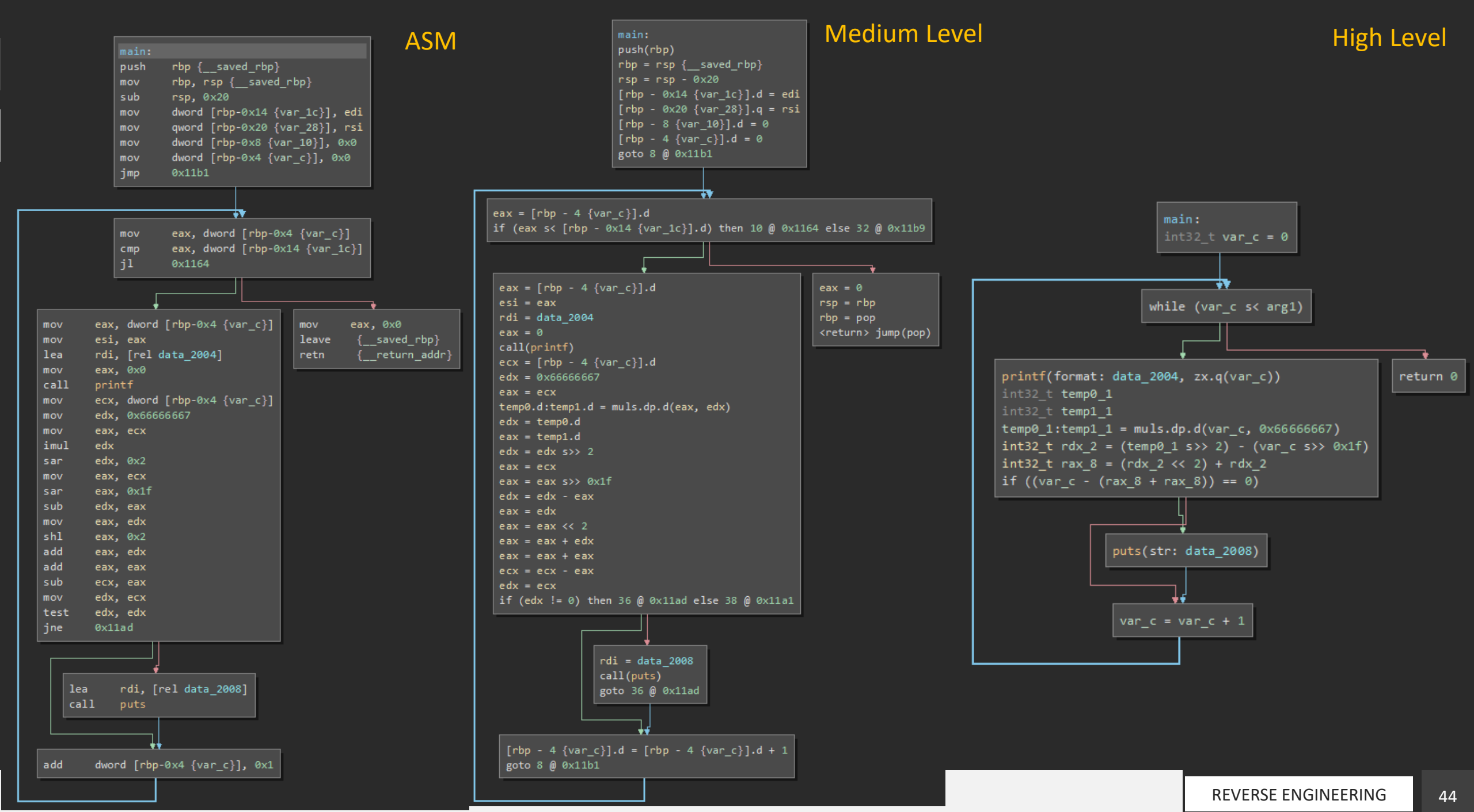


Tools

Decompilers

- Attempt to recover structure at a medium or high level with Static Analysis
  - Result is a pseudo-language (e.g, smali) or pseudo-C
  - Decompilers from bytecode may produce valid code (can be compiled)!
    - Allows Reengineering
  - Process is prone to mistakes, but is extremely useful
    - Researchers do not have to fully understand Assembly (but helps)

- Some relevant tools:
  - dotPeek: .NET decompiler. Fully recovers source code from bytecode
  - Jadx: Java decompiler (fully recovers…)
  - Snowman: ARM, x86, and x86-64 decompiler to pseudo-C
  - ghidra: full disassemble/decompile environment


ASM
Medium Level
High Level
main:
push rbp {__saved_rbp}
mov rbp, rsp {__saved_rbp}
sub rsp, 0x20
mov dword [rbp-0x14 {var_1c}], edi
mov qword [rbp-0x20 {var_28}], rsi
mov dword [rbp-0x8 {var_10}], 0x0
mov dword [rbp-0x4 {var_c}], 0x0
jmp 0x11b1
mov eax, dword [rbp-0x4 {var_c}]
cmp eax, dword [rbp-0x14 {var_1c}]
jl 0x1164
mov eax, dword [rbp-0x4 {var_c}]
mov esi, eax
lea rdi, [rel data_2004]
mov eax, 0x0
call printf
mov ecx, dword [rbp-0x4 {var_c}]
mov edx, 0x66666667
mov eax, ecx
imul edx
sar edx, 0x2
mov eax, ecx
sar eax, 0x1f
sub edx, eax
mov eax, edx
shl eax, 0x2
add eax, edx
add eax, eax
sub ecx, eax
mov edx, ecx
test edx, edx
jne 0x11ad
mov eax, 0x0
leave {__saved_rbp}
retn {__return_addr}
lea rdi, [rel data_2008]
call puts
add dword [rbp-0x4 {var_c}], 0x1
main:
push(rbp)
rbp = rsp {__saved_rbp}
rsp = rsp - 0x20
[rbp - 0x14 {var_1c}].d = edi
[rbp - 0x20 {var_28}].q = rsi
[rbp - 8 {var_10}].d = 0
[rbp - 4 {var_c}].d = 0
goto 8 @ 0x11b1
eax = [rbp - 4 {var_c}].d
if (eax s< [rbp - 0x14 {var_1c}].d) then 10 @ 0x1164 else 32 @ 0x11b9
eax = [rbp - 4 {var_c}].d
esi = eax
rdi = data_2004
eax = 0
call(printf)
ecx = [rbp - 4 {var_c}].d
edx = 0x66666667
eax = ecx
temp0.d:temp1.d = muls.dp.d(eax, edx)
edx = temp0.d
eax = temp1.d
edx = edx s>> 2
eax = ecx
eax = eax s>> 0x1f
edx = edx - eax
eax = edx
eax = eax << 2
eax = eax + edx
eax = eax + eax
ecx = ecx - eax
edx = ecx
if (edx != 0) then 36 @ 0x11ad else 38 @ 0x11a1
eax = 0
rsp = rbp
rbp = pop
<return> jump(pop)
rdi = data_2008
call(puts)
goto 36 @ 0x11ad
[rbp - 4 {var_c}].d = [rbp - 4 {var_c}].d + 1
goto 8 @ 0x11b1
main:
int32_t var_c = 0
while (var_c s< arg1)
printf(format: data_2004, zx.q(var_c))
int32_t temp0_1
int32_t temp1_1
temp0_1:temp1_1 = muls.dp.d(var_c, 0x66666667)
int32_t rdx_2 = (temp0_1 s>> 2) - (var_c s>> 0x1f)
int32_t rax_8 = (rdx_2 << 2) + rdx_2
if ((var_c - (rax_8 + rax_8)) == 0)
puts(str: data_2008)
var_c = var_c + 1
return 0

Pseudo C

```
undefined8 main(int param_1)

{
  uint local_c;

  local_c = 0;
  while ((int)local_c < param_1) {
    printf("%i\n",(ulong)local_c);
    if ((int)local_c % 10 == 0) {
      puts("mod");
    }
    local_c = local_c + 1;
  }
  return 0;
}
```

Original Code

```
int main(int argc, char** argv){

        int i = 0;
        for(int i = 0; i<argc; i++){
                printf("%i\n", i);
                if(i % 10 == 0)
                        printf("mod\n");
        }

        return 0;
}
```

Tools

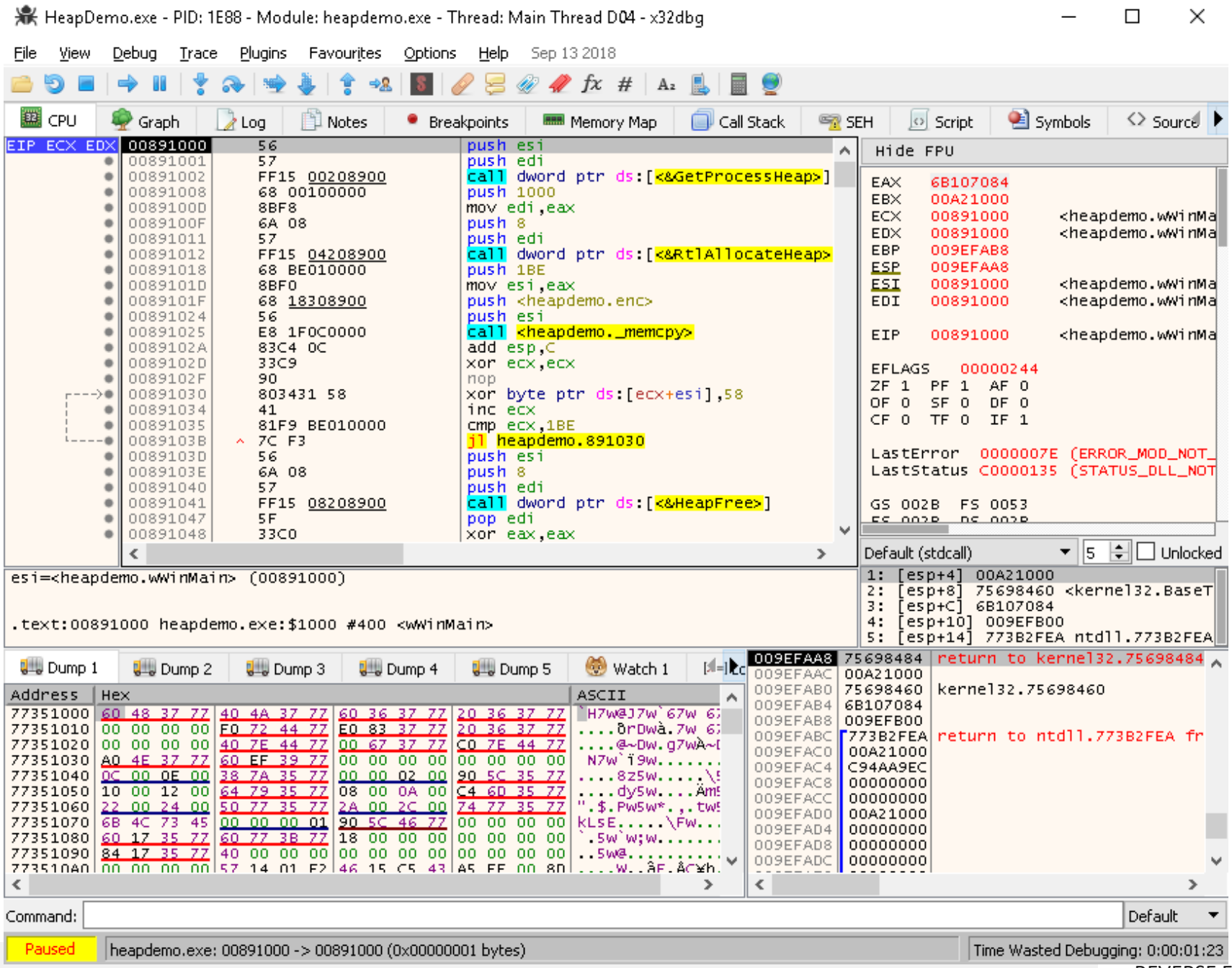
Debuggers

- Enable live inspection of a program through Dynamic Analysis
  - Allow pausing program, changing control flow, inspecting RAM, variables, functions
  - Especially relevant with polymorphic code and unpackers, initial assessments, or debugging own code
    - As it allows to inspect the program behavior
  - May allow remote debugging to embedded systems (e.g, through OpenOCD)

- Some relevant tools:
  - gdb: gnu debugger is a general-purpose debugger for most OS
  - x86dgb: a windows based debugger for x86 and amd64
  - radare2: a multi platform debugger
  - IDA Pro: disassembler, decompiler, debugger

Tools

Debuggers



Tools

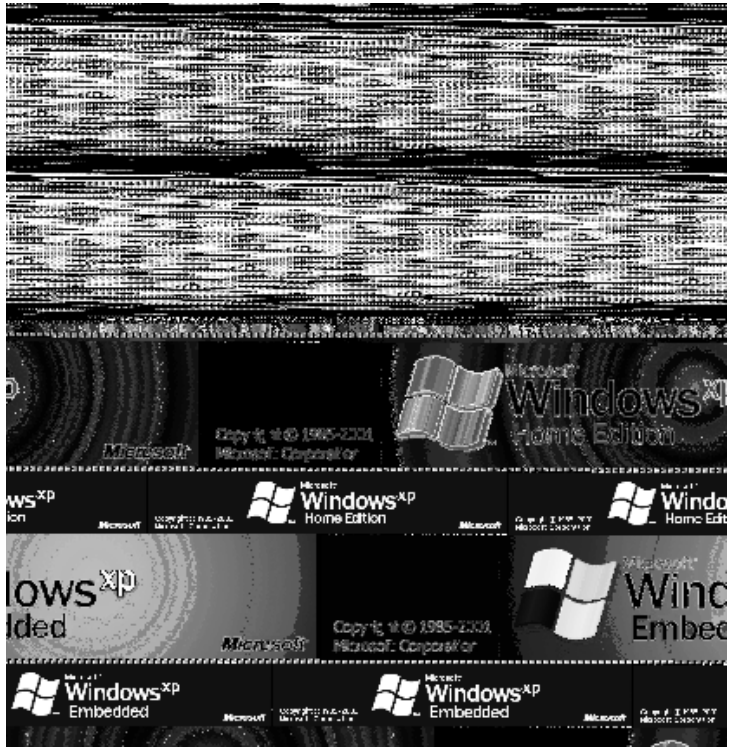
Binary editors, visualizers, extractors

- Directly manipulate files, showing their content
  - May parse known structures and extract data
  - May display entropy maps
  - Allow viewing and editing

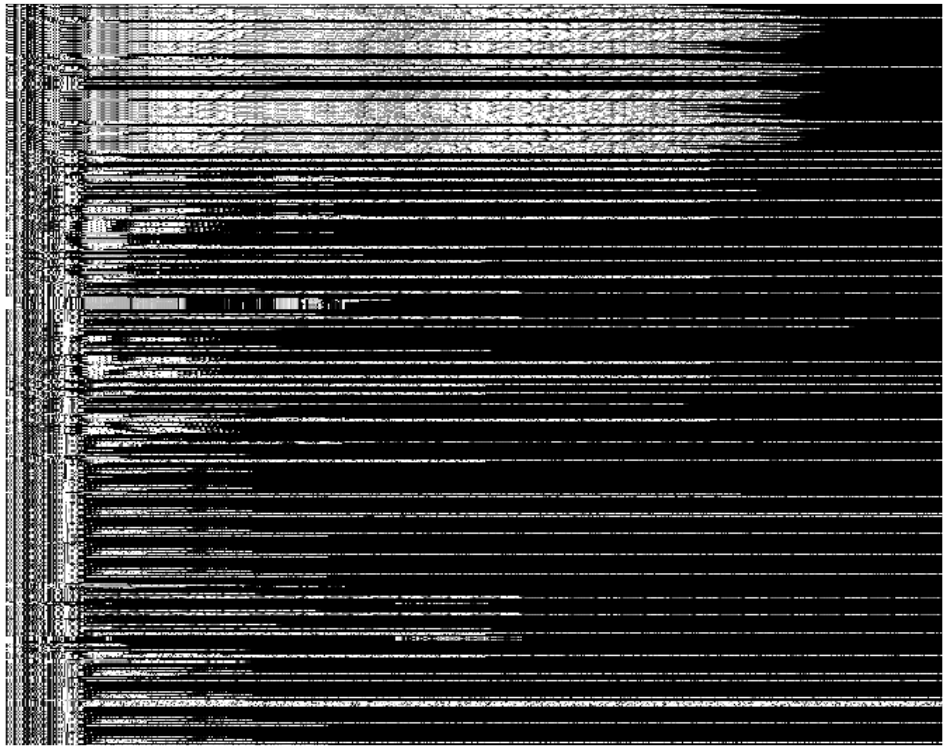
- Some relevant tools
  - Hexdump, hexedit, hexWorkShop: Hex/Text editors
  - Binwalk, foremost: extracts known structures from binary blobs
  - Binvis.io, Veles, Binwalk 3D: allow 2D/3D visualization

Tools

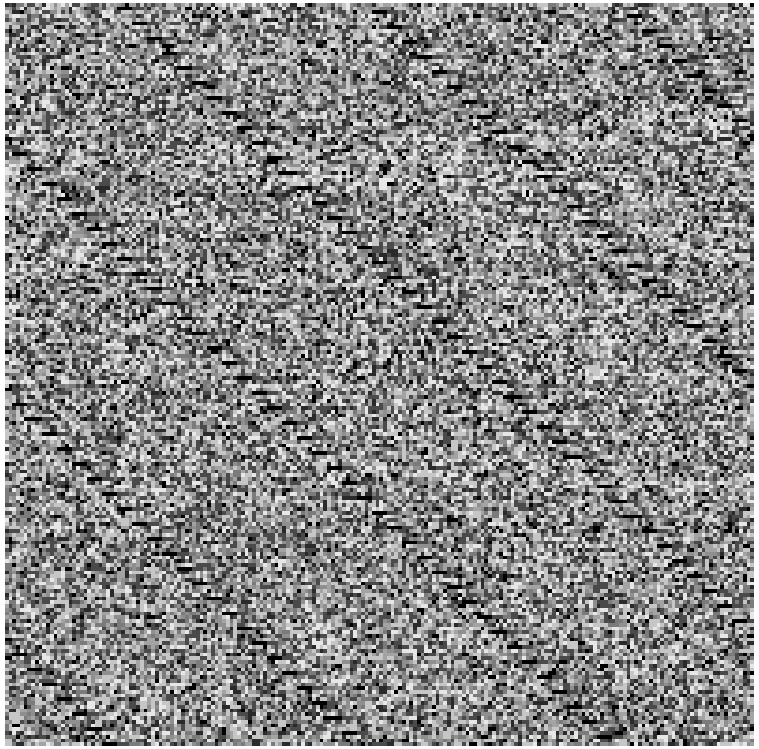
Binary editors, visualizers, extractors



shell32.dll



Network traffic



Compressed data

Greg Conti, Sergei Bratus, “Voyage of the Reverser A Visual Study of Binary Species”

Tools

Binary editors, visualizers, extractors

	Average Byte Value		Shannon Entropy	
		σ		σ
random	127.40	2.34	9.98	0.01
encrypt (AES256/text)	127.47	2.31	9.98	0.01
compress (bzip2/text)	126.68	4.23	9.98	0.01
compress (compress/text)	113.72	8.87	9.96	0.05
compress (deflate (png)	121.78	12.94	9.71	0.70
compress (LZW (gif) / image)	113.75	8.23	9.94	0.05
compress (mpeg/music)	126.26	7.22	9.87	0.44
compress (jpeg/image)	130.76	12.77	9.73	0.88
encoded (base64/zip)	84.46	0.74	9.76	0.02
encoded (uuencoded/zip)	63.71	0.69	9.70	0.02
machine code (linux elf)	116.42	14.97	7.61	0.44
machine code (windows PE)	107.39	18.46	8.06	0.73
bitmap	156.47	69.12	6.22	3.62
text (mixed)	88.52	7.48	7.43	0.24

Greg Conti, Sergei Bratus, “Voyage of the Reverser A Visual Study of Binary Species”