Module Extraction and DLL Hijacking Detection via Single or Multiple Memory Dumps

Pedro Fernández-Álvarez, **Ricardo J. Rodríguez***

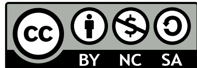
🄯 **All wrongs reversed** – under CC-BY-NC-SA 4.0 license

Universidad Zaragoza

Dept. of Computer Science and Systems Engineering
University of Zaragoza, Spain

March 23, 2023

10th Annual DFRWS Europe Conference
Bonn, Germany



*Corresponding author: rjrodriguez@unizar.es

Outline

1. Introduction
2. Background
3. `Modex` and `Intermodex`
4. Experiments
5. DLL Hijacking Detection
6. Conclusions and Future Work

Universidad Zaragoza

Outline

1 Introduction

2 Background

3 Modex and Intermodex

4 Experiments

5 DLL Hijacking Detection

6 Conclusions and Future Work

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

Introduction

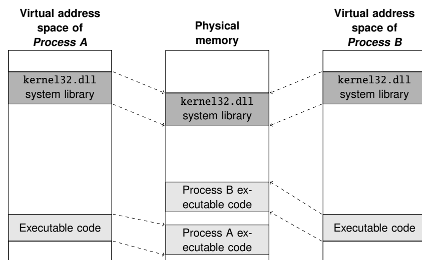
Motivation

Dynamic-Link Library (DLL)

- **Shared library containing functions and data that others can use**
- Helps promote code modularization, code reuse, and efficient memory usage, among other benefits
- It is a **module** (in Windows, *a module is an executable file or DLL*)

Universidad Zaragoza 1542

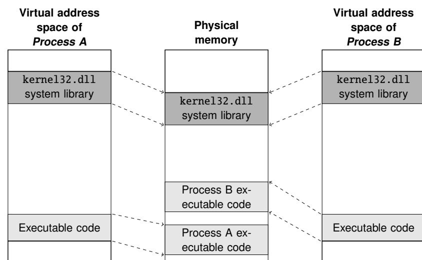
Introduction
Motivation

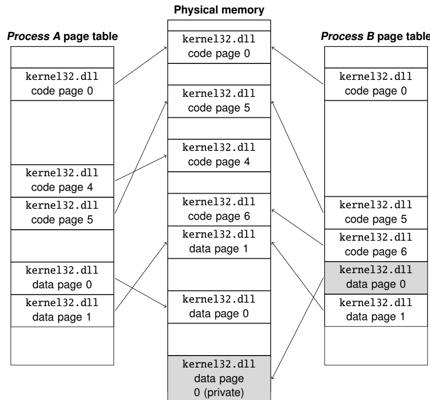


Universidad Zaragoza

Introduction

Motivation



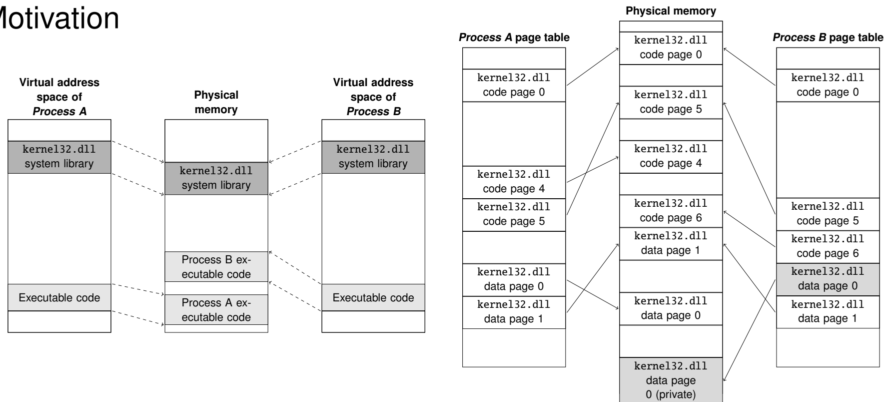


- **Only pages accessed by the process are mapped into virtual memory**
  - A page is *a contiguous block of virtual memory of fixed length* (typically, 4KiB)

Universidad Zaragoza

Introduction

Motivation



- **Only pages accessed by the process are mapped into virtual memory**
  - A page is *a contiguous block of virtual memory of fixed length* (typically, 4KiB)

Limitation of extraction tools: *process-level view*

Current tools for extracting modules from memory dumps only dumps the pages mapped into a single process address space

Introductions

Summary of our contributions

- **New tools to get as much content as possible from a given module**
  - From a single memory dump (***intradump extraction***): `Modex`
  - From multiple memory dump (***interdump extraction***): `Intermodex`
- **Both tools are released under GNU/GPLv3 license at GitHub**
  - Python3-based tools
  - `Modex` is a Volatility 3 plugin, while `Intermodex` is a standalone tool that relies on `Modex`
  - **Create. Share. Build community** ♥
- Relevant to analyze:
  - **Whether a DLL module is malicious or not**
  - **Detection of DLL hijacking attacks**

Universidad Zaragoza

Introductions

Summary of our contributions

- **New tools to get as much content as possible from a given module**
  - From a single memory dump (***intradump extraction***): `Modex`
  - From multiple memory dump (***interdump extraction***): `Intermodex`
- **Both tools are released under GNU/GPLv3 license at GitHub**
  - Python3-based tools
  - `Modex` is a Volatility 3 plugin, while `Intermodex` is a standalone tool that relies on `Modex`
  - **Create. Share. Build community** ♥
- Relevant to analyze:
  - **Whether a DLL module is malicious or not**
  - **Detection of DLL hijacking attacks**

Some remark...

We focus on module extraction of Windows 64-bit DLLs, but our tools are also valid for extracting modules of Windows 64-bit executable files!

Universidad Zaragoza

Outline

1 Introduction

2 Background

3 Modex and Intermodex

4 Experiments

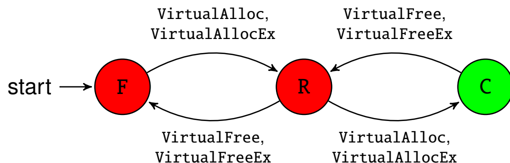
5 DLL Hijacking Detection

6 Conclusions and Future Work

Universidad Zaragoza

Background

On Windows virtual memory management



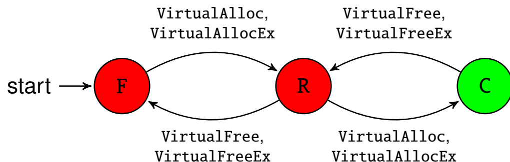
- States of a page: *free*, *reserved*, *committed*

Page Table Entries (PTE)

- Relationship between virtual memory and physical memory

Background

On Windows virtual memory management



- States of a page: *free*, *reserved*, *committed*

Page Table Entries (PTE)

- Relationship between virtual memory and physical memory

Shared vs. private pages ⇔ prototype vs. real/process PTE

- **Shared pages are stored only once in physical memory**
  - **Prototype PTE**: enables shared memory support in Windows
- **Copy-on-write mechanism**
  - Prevents modifications to shared pages from being visible to processes sharing them

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

Background

On Windows virtual memory management

Page frame number database (PFN DB)

- **Windows kernel data structure**
- **Describes each page stored in physical memory** (PFN DB entry)
- Fields of interest:
  - *PteAddress*: contains the virtual address of the PTE
  - *PrototypePTE*: determines whether it is a prototype PTE or not

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

Outline

1 Introduction

2 Background

3 Modex and Intermodex

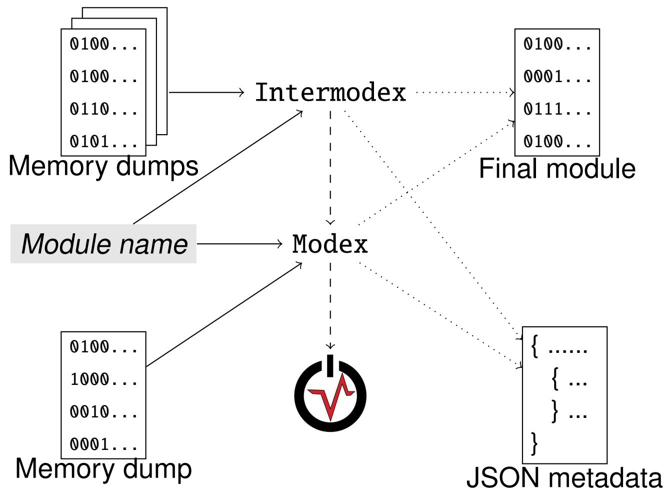
4 Experiments

5 DLL Hijacking Detection

6 Conclusions and Future Work

Universidad Zaragoza

Modex and Intermodex



Universidad Zaragoza

Modex and Intermodex

Implementation details of Modex

- **Volatility 3 plugin**
- **Input**: a memory dump and the module name to be extracted
- **Output**: combined module, JSON file, and an execution log file
- **Workflow**:
  1. Walks through all the processes in the memory dump and checks which one loaded the given module as an argument
  2. It dumps this module, saving it as an *intermediate .dmp* file
  3. Those intermediate *.dmp* files are combined in a single *.dmp* file

Universidad Zaragoza

[CC BY-NC-SA 4.0 ©]

`Modex` and `Intermodex`

Implementation details of `Modex`

- **Volatility 3 plugin**
- **Input**: a memory dump and the module name to be extracted
- **Output**: combined module, JSON file, and an execution log file
- **Workflow**:
  1. Walks through all the processes in the memory dump and checks which one loaded the given module as an argument
  2. It dumps this module, saving it as an *intermediate .dmp* file
  3. Those intermediate *.dmp* files are combined in a single *.dmp* file
- **Third-party dependencies**:
  - `DllList` plugin: to dump modules from processes
  - `SimplePteEnumerator` plugin: to check the *PrototypePTE* flag in PFN DB entries
- **Current limitation**: only works for 64-bit modules

Universidad Zaragoza

Modex and Intermodex

Modex: rules for reconstructing modules

Which page do we choose for the combined module?

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

`Modex` and `Intermodex`

`Modex`: rules for reconstructing modules

Which page do we choose for the combined module?

At a given offset:

- **No page retrieved** → the page is filled with zeroes
- **Only one page is retrieved** → this page is put into the final module

Universidad Zaragoza

Modex and Intermodex

Modex: rules for reconstructing modules

Which page do we choose for the combined module?

At a given offset:

- **No page retrieved** → the page is filled with zeroes
- **Only one page is retrieved** → this page is put into the final module
- **Multiple pages are retrieved**:
  - *All pages are shared*: we choose one of them at random
  - *Some pages are private, some are shared*: we discard the private pages and consider only the shared pages, choosing one of them at random

Universidad Zaragoza

[CC BY-NC-SA 4.0 ©]

Modex and Intermodex

Modex: rules for reconstructing modules

Which page do we choose for the combined module?

At a given offset:

- **No page retrieved** → the page is filled with zeroes
- **Only one page is retrieved** → this page is put into the final module
- **Multiple pages are retrieved**:
  - *All pages are shared*: we choose one of them at random
  - *Some pages are private, some are shared*: we discard the private pages and consider only the shared pages, choosing one of them at random
  - *All pages are private*: we choose the page that most closely resembles the shared page
    - Similarity score (with TLSH) between every two pages to reflect their similarity
    - Recall that the score trend of TLSH is descending
    - Page with the lowest value is chosen as the page to include in the final module

Universidad Zaragoza

Modex and Intermodex

Implementation details of Intermodex

- **Python 3-based tool**
- **Input**: a directory containing multiple memory dumps and the module name
- **Output**: combined module, JSON file, and an execution log file
- It relies on Modex, as Volatility cannot handle multiple dumps at once
- Module reconstruction follows the same rules as Modex
- **Rules for combining modules**:
  - **R1** **Loaded at the same base address**
  - **R2** **With the same path**
  - **R3** **With the same size**
- **Performs also a derelocation process on the extracted module**

Universidad Zaragoza

Outline

1 Introduction

2 Background

3 Modex and Intermodex

4 Experiments

5 DLL Hijacking Detection

6 Conclusions and Future Work

Universidad Zaragoza

Experiments

Methodology

- **VM Windows 10 64-bit** (Pro edition, version 21H2) with 8 GiB of RAM
- **Four applications installed** (most used and most popular):
  - Web browser (`Google Chrome`)
  - Word processor (`Microsoft Word`)
  - PDF reader (`Adobe Acrobat Reader DC`)
  - Spreadsheet processor (`Microsoft Excel`)
- **Simulation of user behavior in steps** (power on, web browsing, view PDFs, creation of Word and Excel documents)
- Each application is used for 5 minutes. **Two experimental scenarios**:
  1. Applications are not closed after using them
  2. Applications are closed after using them

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

Experiments
Methodology

- **Memory dumps collected after each user step** (10 in total)
- **Subset of DLLs loaded by all the applications**
  - `ntdll.dll`, `user32.dll`, `ole32.dll`, `kernel32.dll`, `advapi32.dll`, and `gdi32.dll`

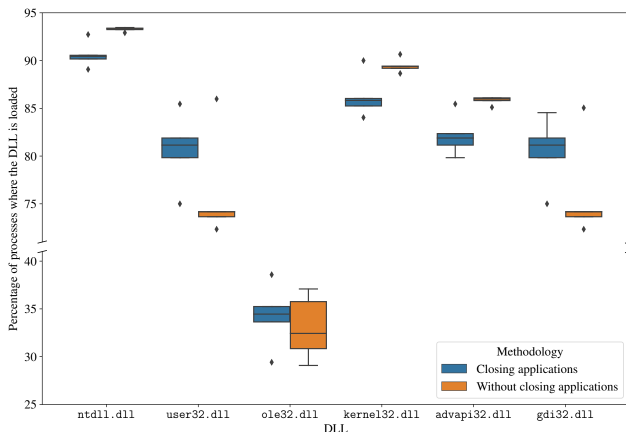
For each DLL and scenario:

- `Modex` on the first memory dump
- `Intermodex` on the first and second memory dumps
- `Intermodex` on the first, second, and third memory dumps
- ... *(until we consider all five memory dumps)*

Universidad Zaragoza

Experiments

Use of selected DLLs in multiple processes

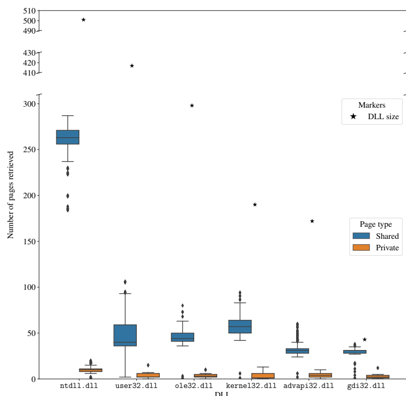


All of them (except `ole32.dll`) are loaded by a large no. processes

Universidad Zaragoza

Experiments

Intradump extraction

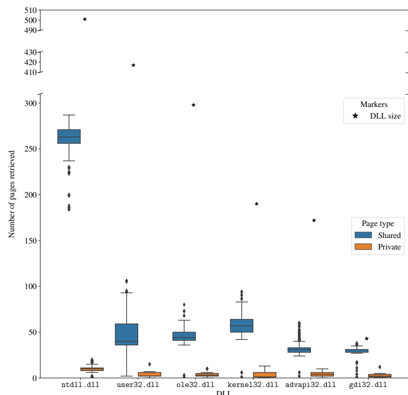


(a) Without combining pages

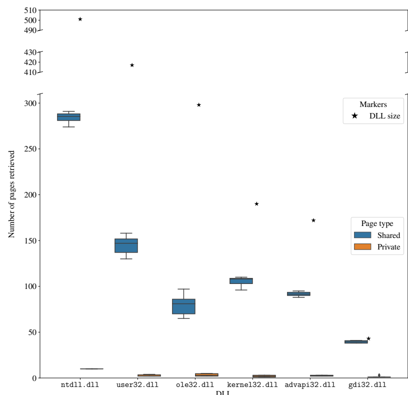
- Only the mapped pages on the address space of a process can be retrieved
- **No. shared pages is greater than the no. private pages for all modules**

Experiments

Intradump extraction



(a) Without combining pages



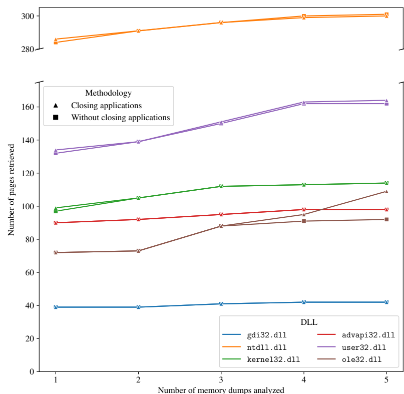
(b) Combining pages

- **Combined module contains more pages in all cases**
- **No. private pages decreases when modules are combined** (as shared pages take precedence over private pages by our implementation)

Universidad Zaragoza

Experiments

Interdump extraction

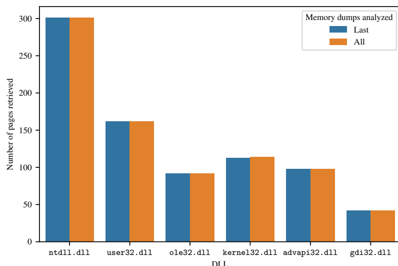


- **Results in both scenarios are very similar**, with slightly variations
  - Behavior of `ole32.dll` can be caused by many factors
- **More complete modules are obtained by combining pages and memory dumps**

Universidad Zaragoza

Experiments

No. pages considering the last or all memory dumps



(a) Without closing applications

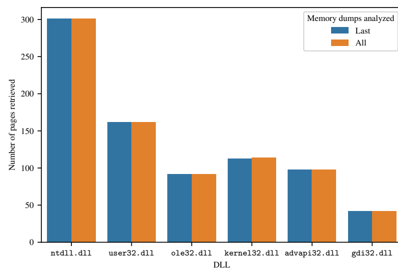
- **In the first scenario, practically no difference**
  - The same content was in memory in both situations because the apps were not closed

Universidad Zaragoza

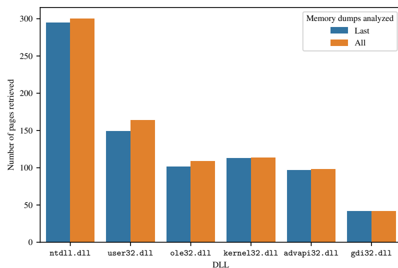
 [CC BY-NC-SA 4.0 ©]

Experiments

No. pages considering the last or all memory dumps



(a) Without closing applications



(b) Closing applications

- **In the first scenario, practically no difference**
  - The same content was in memory in both situations because the apps were not closed
- **In the second scenario, more memory dumps is clearly beneficial**
  - No. pages retrieved is slightly higher considering all vs. just the last memory dump
  - We expected these differences to be larger... ☹

Universidad Zaragoza

Experiments

No. pages considering the last or all memory dumps

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

Experiments

Interesting findings and limitations

- **Some pages marked as shared and owned by a DLL, loaded at the same base address in multiple processes, but with different content**
  - Found in DLLs other than the ones used for experimentation
  - We manually verified the differences in **these pages correspond to memory addresses stored within those pages**
  - **This happens very rarely**. We treat it as an anomaly and implement functionality to analyze it. When found, we choose the most repeated shared page

Universidad Zaragoza

Experiments

Interesting findings and limitations

- **Some pages marked as shared and owned by a DLL, loaded at the same base address in multiple processes, but with different content**
  - Found in DLLs other than the ones used for experimentation
  - We manually verified the differences in **these pages correspond to memory addresses stored within those pages**
  - **This happens very rarely**. We treat it as an anomaly and implement functionality to analyze it. When found, we choose the most repeated shared page

Limitations

- **Base addresses of the modules must be the same to be combined**
  - A page-granularity level derelocation process is required to normalize the page content before combining the dumped modules (future work)

Universidad Zaragoza

Outline

1 Introduction

2 Background

3 Modex and Intermodex

4 Experiments

5 DLL Hijacking Detection

6 Conclusions and Future Work

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

DLL Hijacking Detection

Background on hijacking execution flow attacks

- **Different purposes**:
  - Persistence
  - Escalating privileges
  - Hiding malicious actions behind a legitimate process
- **DLL search order hijacking**:
  - Adversaries take advantage of the Windows DLL search order to make a particular program load a malicious DLL
  - The malicious DLL must have the same filename as the legitimate one, and also the same exported function names
  - These functions must work as the originals, so that the program can run as usual
  - ***DLL proxying*: acts as a proxy between the program and the legitimate DLL**
    - A well-known malware that uses this technique is Stuxnet

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

DLL Hijacking Detection

- `--detect` flag
  - No module is extracted in this case
  - The JSON file provided as output contains information about the detection of DLL hijacking techniques
  - `Modex` indicates the affected processes, while `Intermodex` also indicates the affected memory dumps
- **Module path and size in all processes that contains it are compared**
  - Actual path and size are those that are most common for all the modules found
  - We assume that the processes targeted by DLL hijacking techniques are a minority
- **DLL hijacking detected when at least one path is different from the most common path or at least one size is different from the most common size**
  - **Disadvantage**: it will not detect the attack when the paths and sizes of the malicious DLL and the legitimate DLL match

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

DLL Hijacking Detection

- `--detect` flag
  - No module is extracted in this case
  - The JSON file provided as output contains information about the detection of DLL hijacking techniques
  - `Modex` indicates the affected processes, while `Intermodex` also indicates the affected memory dumps
- **Module path and size in all processes that contains it are compared**
  - Actual path and size are those that are most common for all the modules found
  - We assume that the processes targeted by DLL hijacking techniques are a minority
- **DLL hijacking detected when at least one path is different from the most common path or at least one size is different from the most common size**
  - **Disadvantage**: it will not detect the attack when the paths and sizes of the malicious DLL and the legitimate DLL match
- **Limitations**
  - **Our tools need a DLL name**. As future work, we will integrate this feature directly in `Modex` and `Intermodex`
  - **We focus exclusively on 64-bit processes**
  - **If the hijacked DLL is loaded only in a single process, there would be no other processes to compare against**

Universidad Zaragoza

 [CC BY-NC-SA 4.0 ©]

DLL Hijacking Detection

- PoC performing DLL proxying on `cryptbase.dll`
- `VLC media player` as victim application

```
{
    "memory_dump_location": "file:///tmp/MemoryDumps/
       InfectedDump.elf",
    "mapped_modules": [
        ...
    ],
    "dll_hijacking_detection_result": true,
    "suspicious_processes": [
        3208
    ]
}
```

Code 1: DLL hijacking detection of our PoC with `Modex`.

```
{
    "dll_hijacking_detection_result": true,
    "suspicious_processes": {
        "file:///tmp/MemoryDumps/InfectedDump.elf": [
            3208
        ]
    }
}
```

Code 2: DLL hijacking detection of our PoC with `Intermodex`.

Universidad Zaragoza

Outline

1 Introduction

2 Background

3 Modex and Intermodex

4 Experiments

5 DLL Hijacking Detection

6 Conclusions and Future Work

Universidad Zaragoza

Conclusions and Future Work

- **Two tools to extract a module as complete as possible from memory**
  - `Modex`: a Volatility 3 plugin that combines the pages of the same module that are mapped in different processes from a single Windows memory dump (*intradump extraction*)
  - `Intermodex`: it does the same, but with multiple memory dumps (*interdump* extraction)
- **Available under the GNU/GPLv3 license at GitHub**
- **Functionality to detect DLL hijacking attacks**

Universidad Zaragoza

Conclusions and Future Work

- **Two tools to extract a module as complete as possible from memory**
  - `Modex`: a Volatility 3 plugin that combines the pages of the same module that are mapped in different processes from a single Windows memory dump (*intradump extraction*)
  - `Intermodex`: it does the same, but with multiple memory dumps (*interdump* extraction)
- **Available under the GNU/GPLv3 license at GitHub**
- **Functionality to detect DLL hijacking attacks**

Future work

- *How to combine the same modules with different base addresses?*
  - Theoretically, simply apply derelocation on the intermediate .dmp files. In practice...
- *Extend our tools to detect other DLL injection techniques*
- *Can we extract more content from packed malware modules using interdump extraction?*

Universidad Zaragoza

Module Extraction and DLL Hijacking Detection via Single or Multiple Memory Dumps

Pedro Fernández-Álvarez, **Ricardo J. Rodríguez***

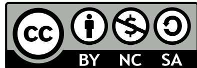
🄯 **All wrongs reversed** – under CC-BY-NC-SA 4.0 license

Universidad Zaragoza

Dept. of Computer Science and Systems Engineering
University of Zaragoza, Spain

March 23, 2023

10th Annual DFRWS Europe Conference
Bonn, Germany



*Corresponding author: rjrodriguez@unizar.es