CodeFlowVis

Visualizer of Code Coverage and Execution Flow

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Background

- **Code Coverage**
  - Executed source code during the testing
  - Useful in identifying errors or vulnerabilities

```
int main(){
    int a = input();
    int b = 2;
    if (a > b){
        a = a + 1;
    } else {
        b = b + 1;
    }
    return b;
}
```

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```

a = 1

Background

- **Code Coverage**
  - Executed source code during the testing
  - Useful in identifying errors or vulnerabilities
- **Code Coverage Tools**
  - JaCoCo[1], GCOV[2]
  - Measure & Visualize code coverage

```c
int main(){
    int a = input();
    int b = 2;
    if (a > b){
        a = a + 1;
    } else {
        b = b + 1;
    }
    return b;
}
```

a = 1

```
-:    0:Runs:2
-:    1:#include <stdio.h>
-:    2:
2:    3:void print_hello(){
2:    4:    printf("hello, world!\n");
2:    4-block  0
2:    5:}
-:    6:
2:    7:int main(){
2:    8:    print_hello();
2:    8-block  0
2:    9:    return 0;
-:   10:}
```

[1] JaCoCo, https://www.jacoco.org/jacoco/
[2] GCOV, https://gcc.gnu.org/onlinedocs/gcc/Gcov.html

Problem

- Difficult to identify the **execution flow**
- It is easy when it is a single function & file.

```
int main(){
    int a = input();
    int b = 2;
    if (a > b){
        f();
    } else {
        g();
    }
    return b;
}
```

a = 1

Problem

- Difficult to identify the **execution flow**
- It is easy when it is a single function & file

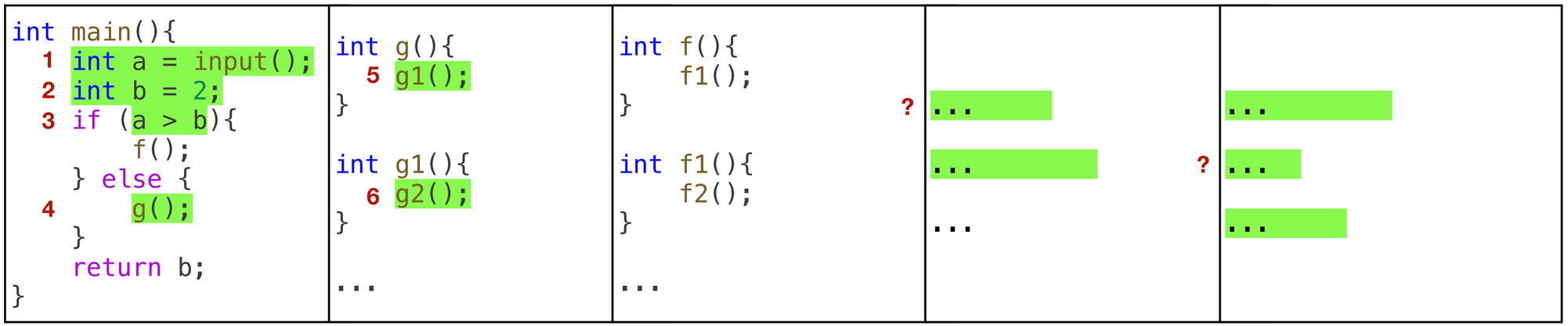
```
int main(){
  1 int a = input();
  2 int b = 2;
  3 if (a > b){
        f();
    } else {
  4     g();
    }
    return b;
}
```

main.c

a = 1

Problem

- Difficult to identify the **execution flow**
- It is easy when it is a single function & file
- But It's hard when there are complex and big codes



Problem

- Difficult to identify the execution flow
- It is easy when it is a single function & file.
- But it is hard when there are complex and big codes.

Why is it important to know the **execution flow**?

```
int main(){
    int a = input();
    int b = 2;
    if (a > b){
        f();
    } else {
        g();
    }
    return b;
}
```

```
int f(){
    f1();
}

int f1(){
    f2();
}

...
```

```
int g(){
    g1();
}

int g1(){
    g2();
}

...
```

```
...

...

...
```

```
...

...

...
```

a = 1

Importance of Execution Flow

- It's difficult to pinpoint exactly **where** and **why** a bug occurs when it arises
- Debugging is challenging
  - understanding the detailed cause of the issue is difficult
- Sometimes, it's impossible to determine why the error occurred
- Therefore, we need to know the **execution flow**

Example

- CVE-2017-14940[3]
  - nm (GNU Binary Utilities), binutils-2.29
  - Denial of Service

Agostino Sarubbo 2017-09-21 12:47:50 UTC Description

Created attachment 10436 [details]
screenshot of the issue

To reproduce:
```
# nm -A -a -l -S -s --special-syms --synthetic --with-symbol-versions -D $FILE
```

I don't get failures but it eats ~230GB of ram.

```
# nm -V
GNU nm (Gentoo git) 2.29.51.20170921
```

[3] CVE-2017-14940, https://nvd.nist.gov/vuln/detail/CVE-2017-14940

Example

- CVE-2017-14940 Demo

Example

- In this bug case,
  - No stack trace log
  - No debug information
  - But, the binutils codebase has almost 5 million lines

Example

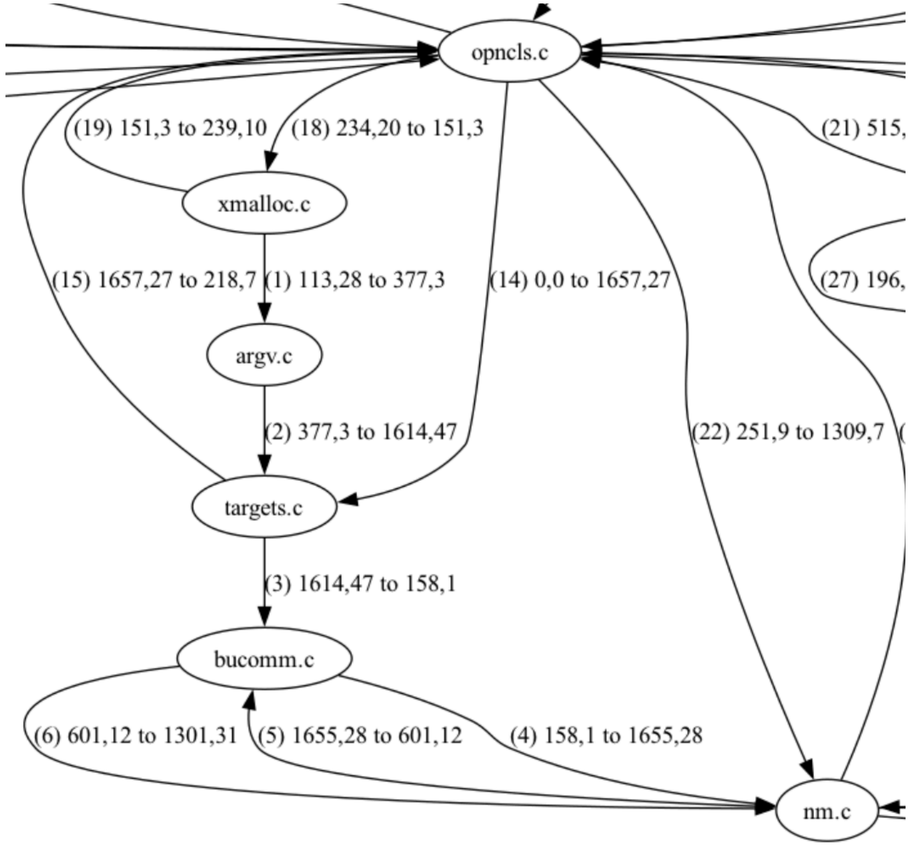
- In this bug case,
  - No stack trace log
  - No debug information
  - But, the binutils codebase has almost 5 million lines

How can we debug and fix this bug?

CodeFlowVis

- Provides code coverage and execution flow results at the same time
- Can know what code a particular input went through when an error occurred
  - Based on VSCode, LLVM

CodeFlowVis

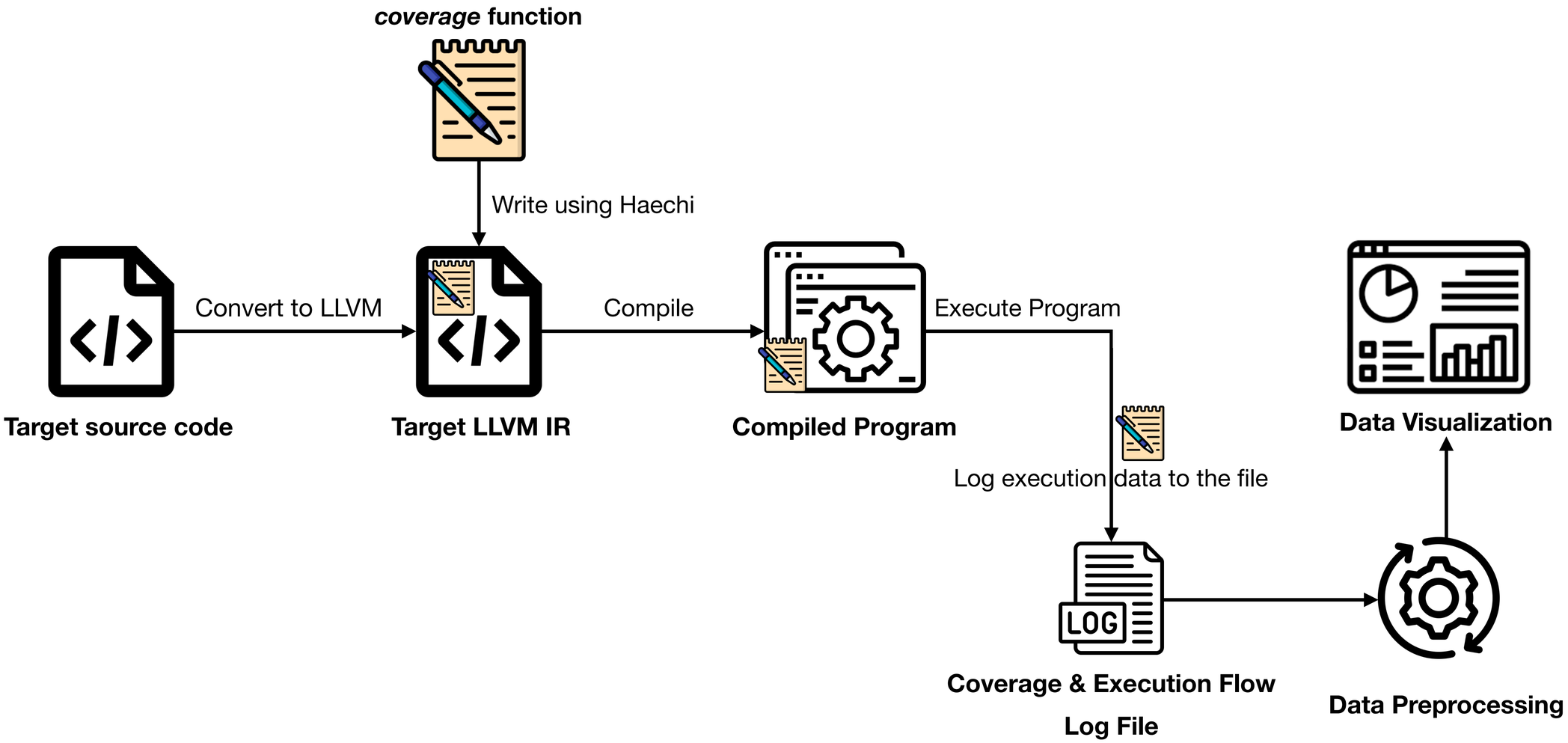


State transition diagram

```
24 1301   file = bfd_openr (filename, target ? target : plugin_target);
   1302   if (file == NULL)
   1303     {
   1304       bfd_nonfatal (filename);
   1305       return FALSE;
   1306     }
   1307
   1308   /* If printing line numbers, decompress the debug sections.  */
67 1309   if (line_numbers)
68 1310     file->flags |= BFD_DECOMPRESS;
   1311
69 1312   if (bfd_check_format (file, bfd_archive))
   1313     {
   1314       display_archive (file);
   1315     }
   1316   else if (bfd_check_format_matches (file, bfd_object, &matching))
   1317     {
   1318       set_print_width (file);
416 1319       format->print_object_filename (filename);
```

Highlighting in VSCode

Overview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Coverage & Execution Flow Log File
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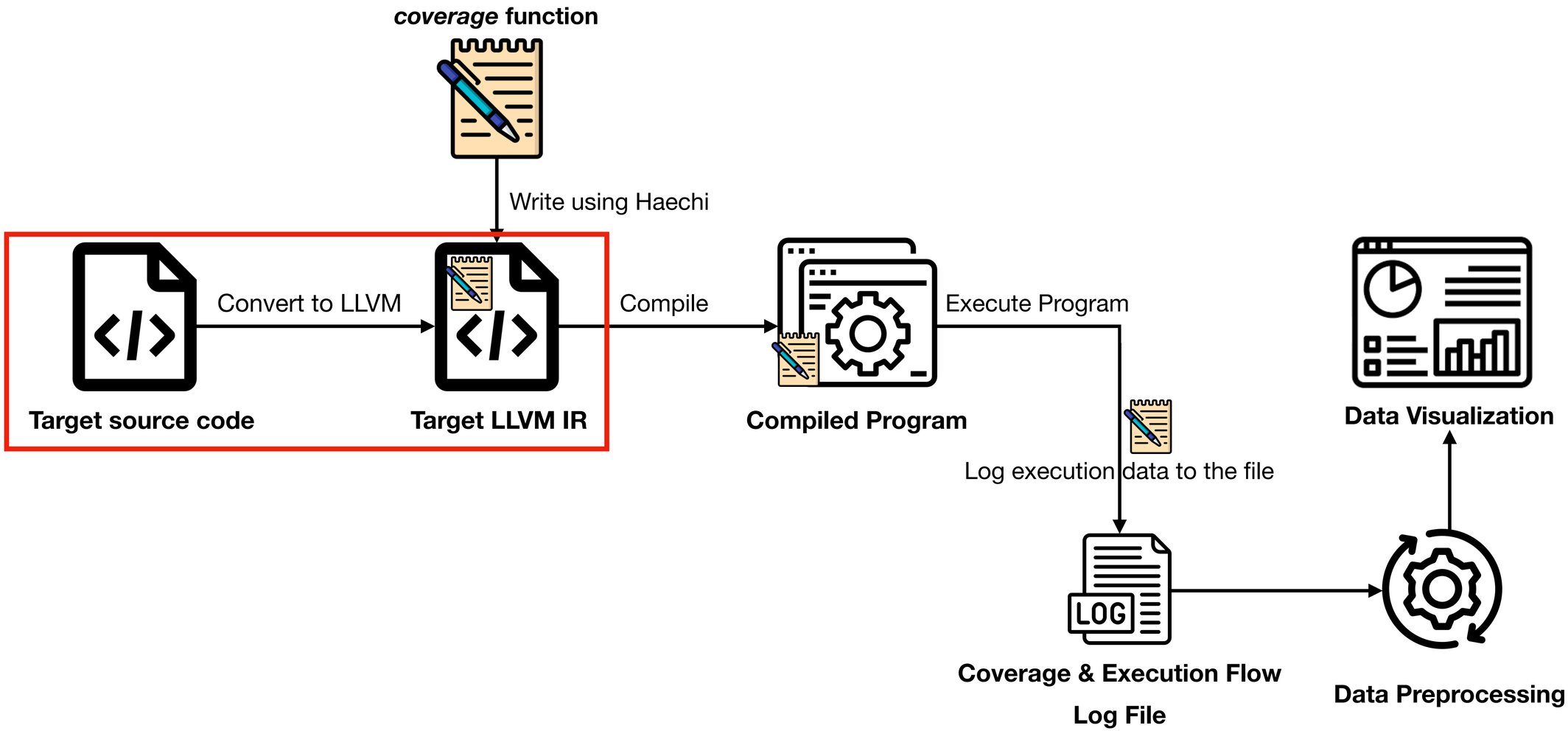
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Convert to LLVM IR

- We collect information by inserting instrumentation based on LLVM
  - We chose LLVM because it supports various platforms
- For a single file, you can convert it to LLVM IR using the *clang* tool
- However, converting an entire project to LLVM is a challenging task
- To solve this problem, we use gllvm[4]

[4] gllvm, https://github.com/SRI-CSL/gllvm

GLLVM?

- Generate LLVM bitcode from C/C++ projects
- Replace the compiler with ***gclang***
- Use ***get-bc*** to extract bitcode

Convert to LLVM IR

- You just need to use *gclang* as the compiler
- You can obtain the bitcode by using *get-bc*
- You can convert the bitcode to LLVM IR with *llvm-dis*
- Through this process, you can convert the entire project to LLVM IR

Convert to LLVM IR

- You just need to use *gclang* as the compiler
- You can obtain the bitcode by using *get-bc*
- You can convert the bitcode to LLVM IR with *llvm-dis*
- Through this process, you can convert the entire project to LLVM IR

```
CC=gclang CXX=gclang++ ./configure $CONFIG_OPTIONS || exit 1
CC=gclang CXX=gclang++ make -j || exit 1
```

Compile with *gclang*

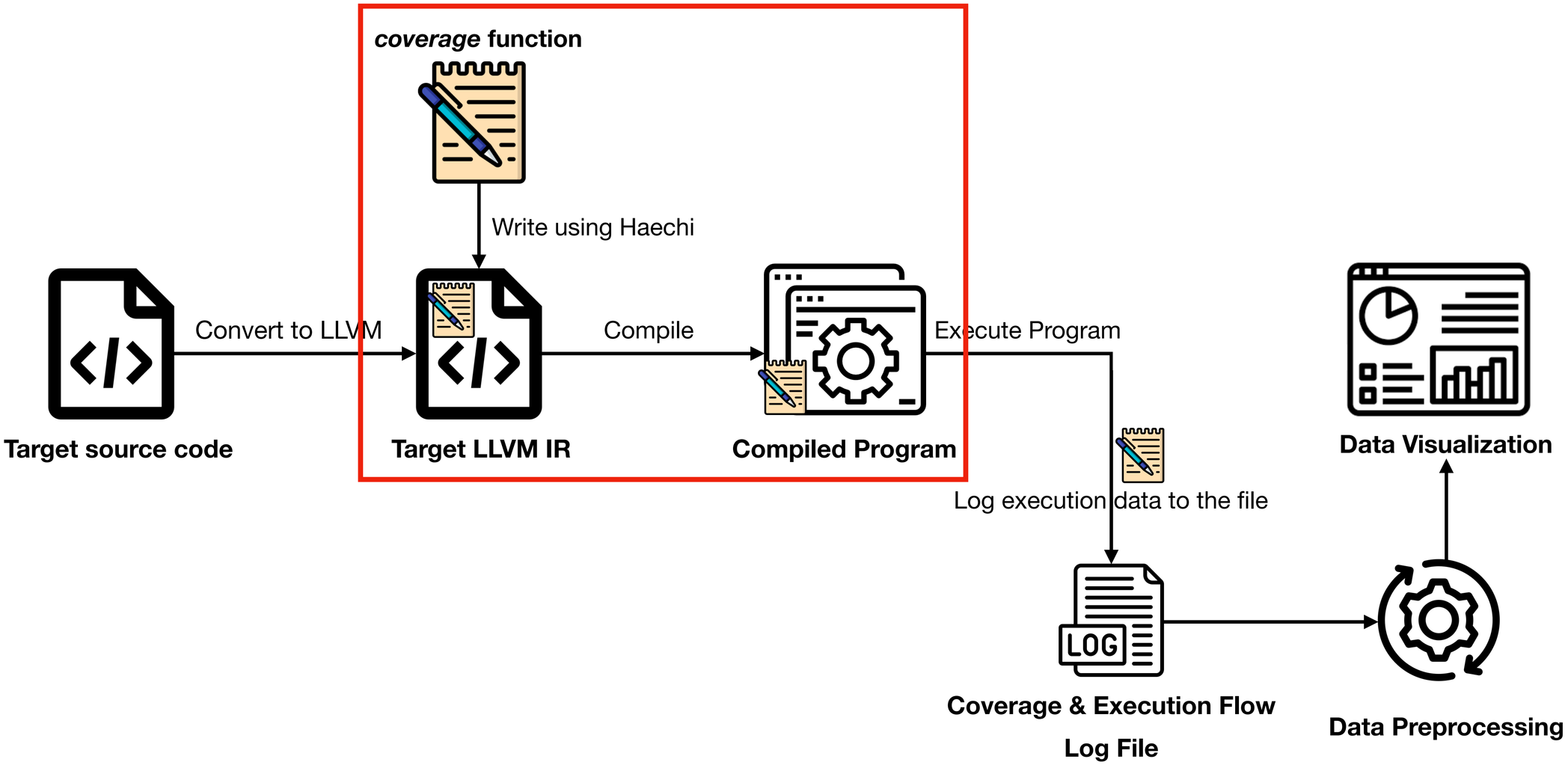
```
root@c2617159fea5:/benchmark/project/binutils-2.29# get-bc nm-haechi
Bitcode file extracted to: nm-haechi.bc.
```

Get bitcode with *get-bc*

```
root@c2617159fea5:/benchmark/project/binutils-2.29# llvm-dis-12 nm-haechi.bc
root@c2617159fea5:/benchmark/project/binutils-2.29# ll nm-haechi.ll
-rw-r--r-- 1 root root 47684731 May 15 04:01 nm-haechi.ll
```

Get readable LLVM with *llvm-dis*

Overview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Insert Coverage Function

- Define the coverage function in C
- Insert this function into the target LLVM IR
- Compile the LLVM IR with the inserted instrumentation

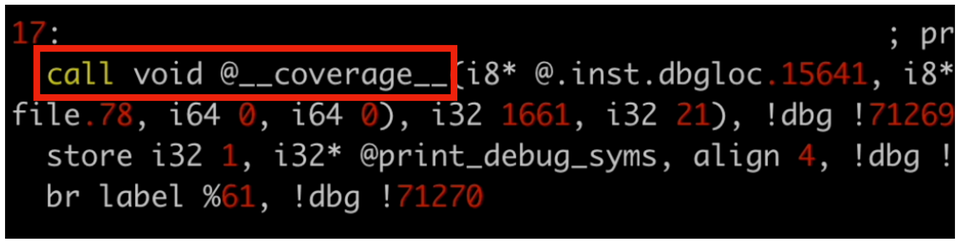
Insert Coverage Function

- Define the coverage function in C
  - Define the *__coverage__* function in a C file
  - It takes *filename*, *line*, and *col* as inputs
  - Saves them to a file
    - [filename]:[line],[col]
    - objcopy.c:152,10

```
void __coverage__(
  char *checked,
  char *filename,
  int line,
  int col)
```

Insert Coverage Function

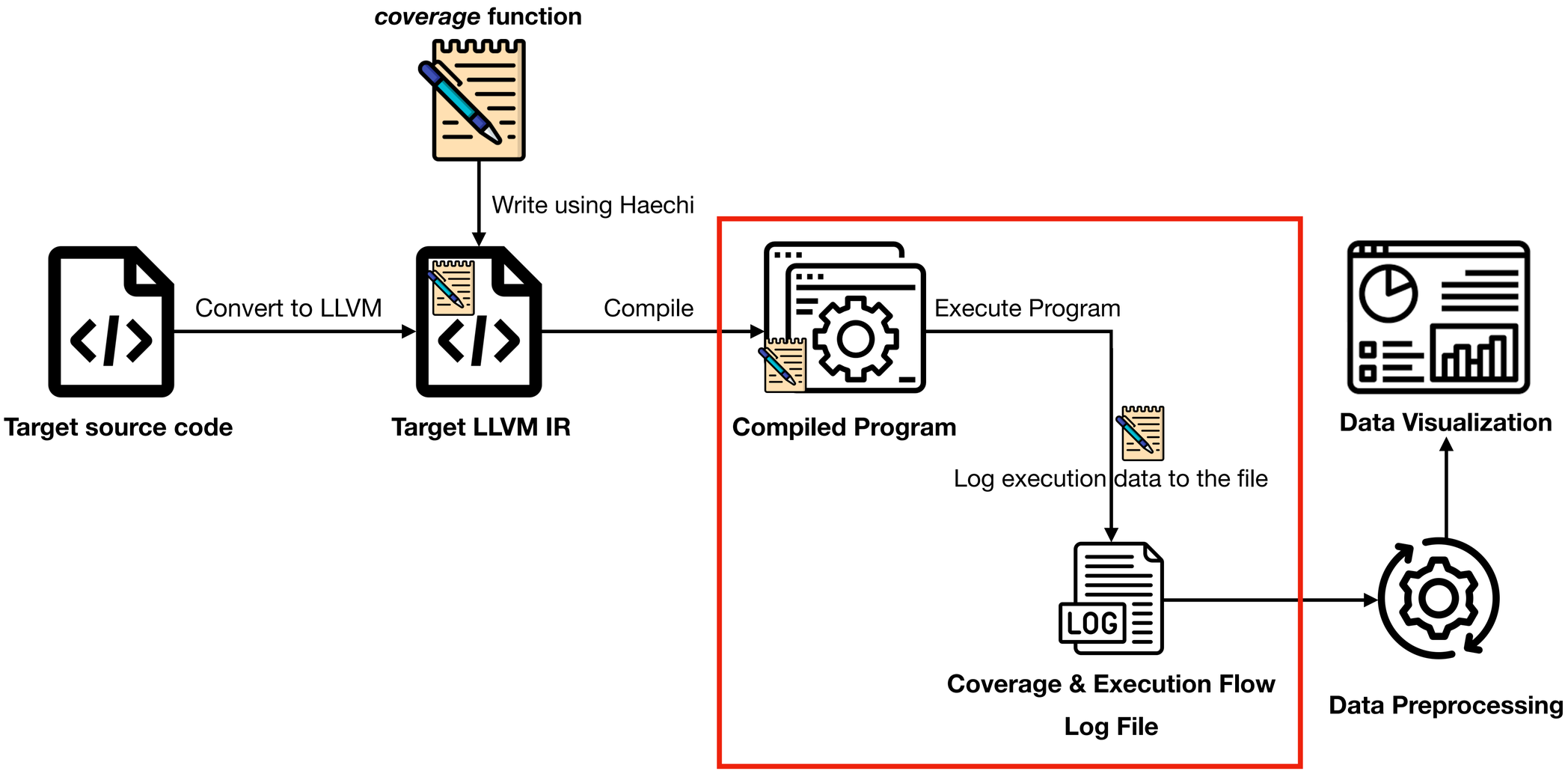
- Insert this function into the target LLVM IR
  - Traverse the entire LLVM IR
    - Insert a "*call __coverage__*" function for every instruction
- Retrieve the filename and line number using the LLVM API



Insert Coverage Function

- Compile the LLVM IR with the inserted instrumentation
  - The coverage function is an external function
    - so it goes through the linking process
    - *llvm-link*
  - The instrumented binary is compiled by
    - *gclang*
- This feature is implemented using a static analysis tool called *Haechi* in our lab

Overview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Execute Program

- Execute the binary obtained through the previous process
- After execution, data is recorded by the coverage function inserted by Haechi
- The data is saved to a *.cov* file
- The format is [filename]:[line],[column]

```
nm.c:1301,31
opncls.c:62,18
libbfd.c:193,9
libbfd.c:281,5
libbfd.c:283,3
opncls.c:66,7
```

.cov file example

Execute Program

- Execute the binary obtained through the previous process
- After execution, data is recorded by the coverage function inserted by Haechi
- The data is saved to a *.cov* file
- The format is [filename]:[line],[column]
  - capturing both coverage and execution flow
  - The execution flow can be determined
    - by the order in which the data is saved

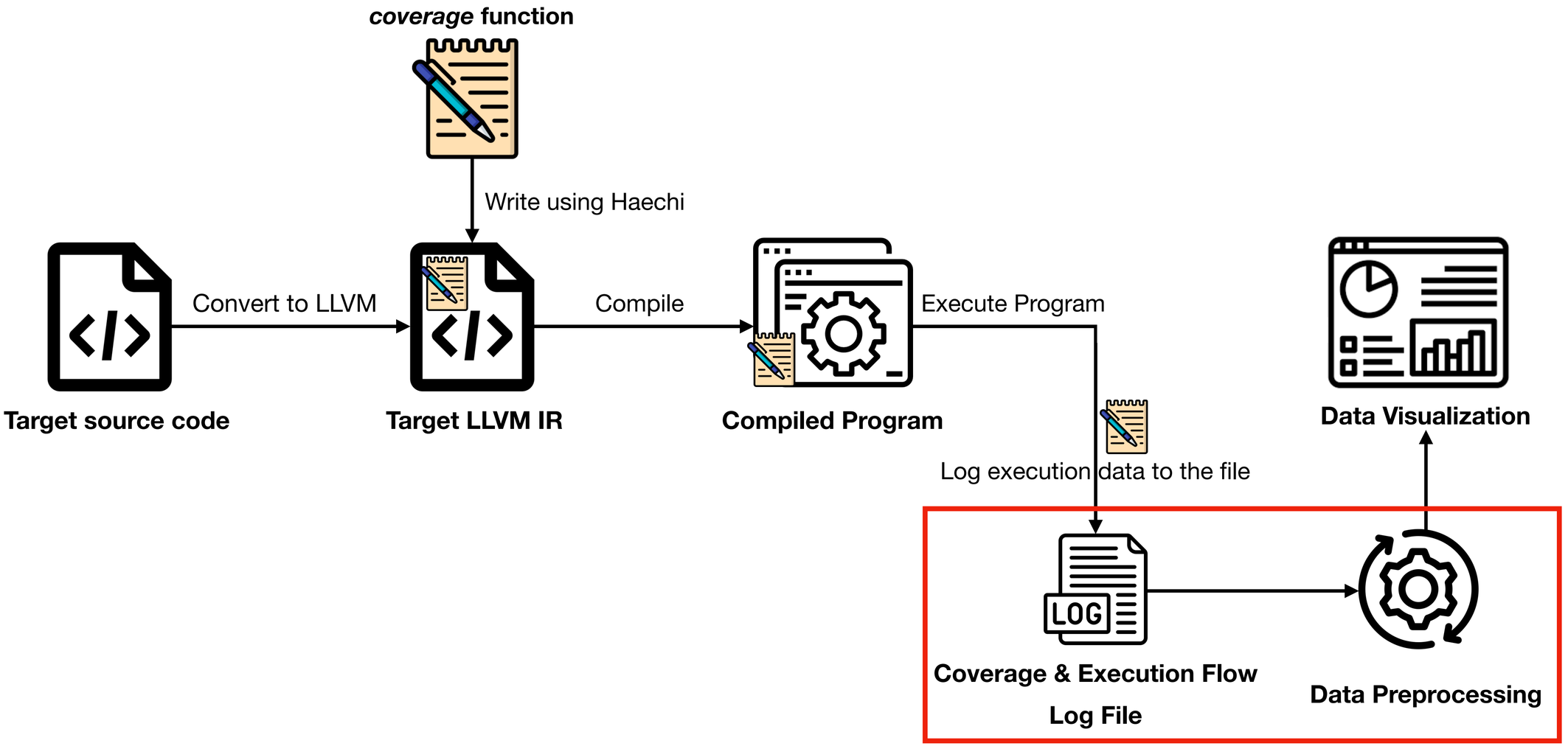
```
1 nm.c:1301,31
2 opncls.c:62,18
3 libbfd.c:193,9
4 libbfd.c:281,5
5 libbfd.c:283,3
6 opncls.c:66,7
```

.cov file example

Execute Program

- I will demonstrate the entire process in a video

Overview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Data Preprocessing

- The generated .cov file goes through two main processes

1. Change the filename to the project path
2. Generate a State Transition Diagram

- This process is performed using a python script
  - Run the script with
  - python3 *process_cov_file.py* [cov filename] [project path]

Data Preprocessing

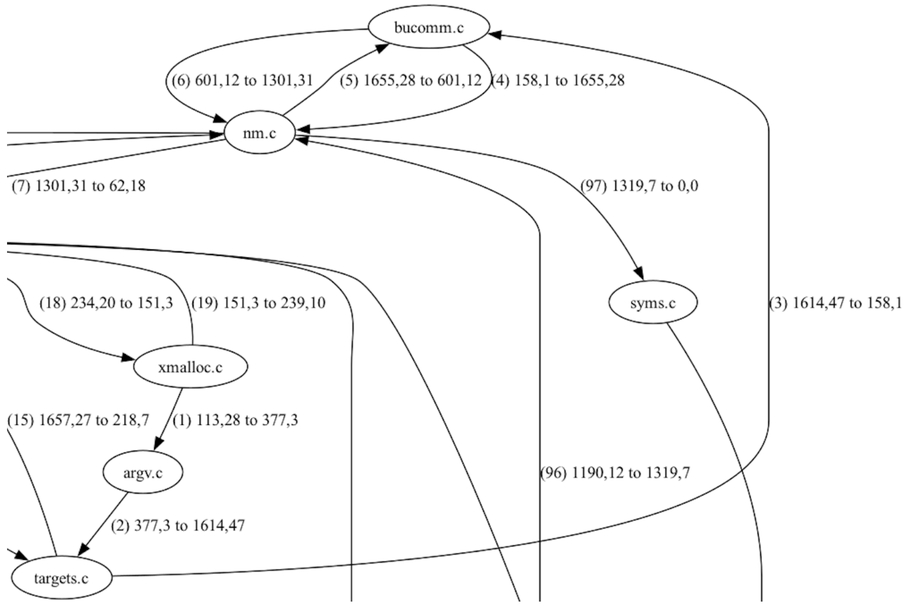
1. Change the filename to the project path
   - This is for highlighting later

Data Preprocessing

2. Generate a State Transition Diagram
   - Generate a state transition diagram to visualize the overall flow
   - with *graphviz* python module

```
libiberty/argv.c:377,3
bfd/targets.c:1614,47
bfd/targets.c:1581,67
binutils/bucomm.c:158,1
binutils/nm.c:1655,28
```

Preprocess



Data Preprocessing

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.cov file

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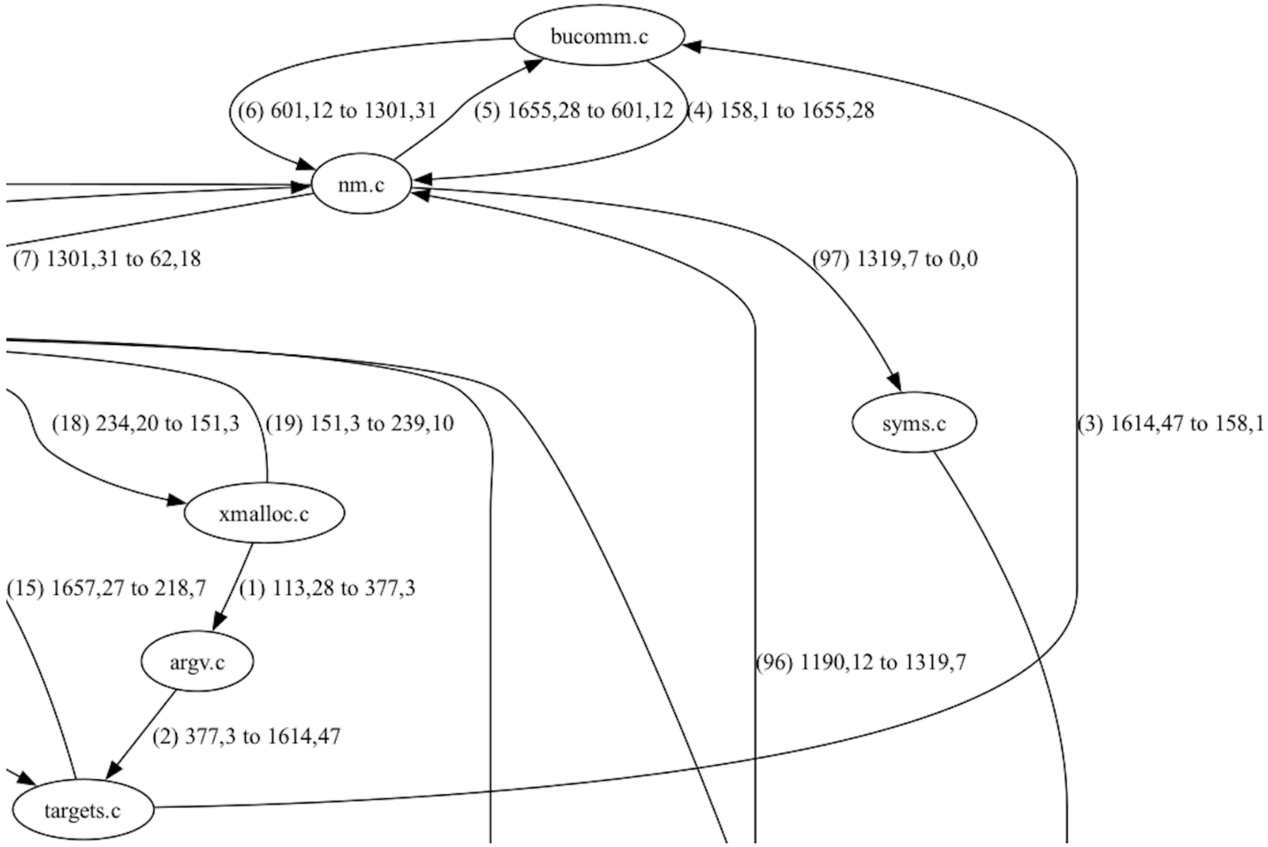

State transition diagram

Data Preprocessing

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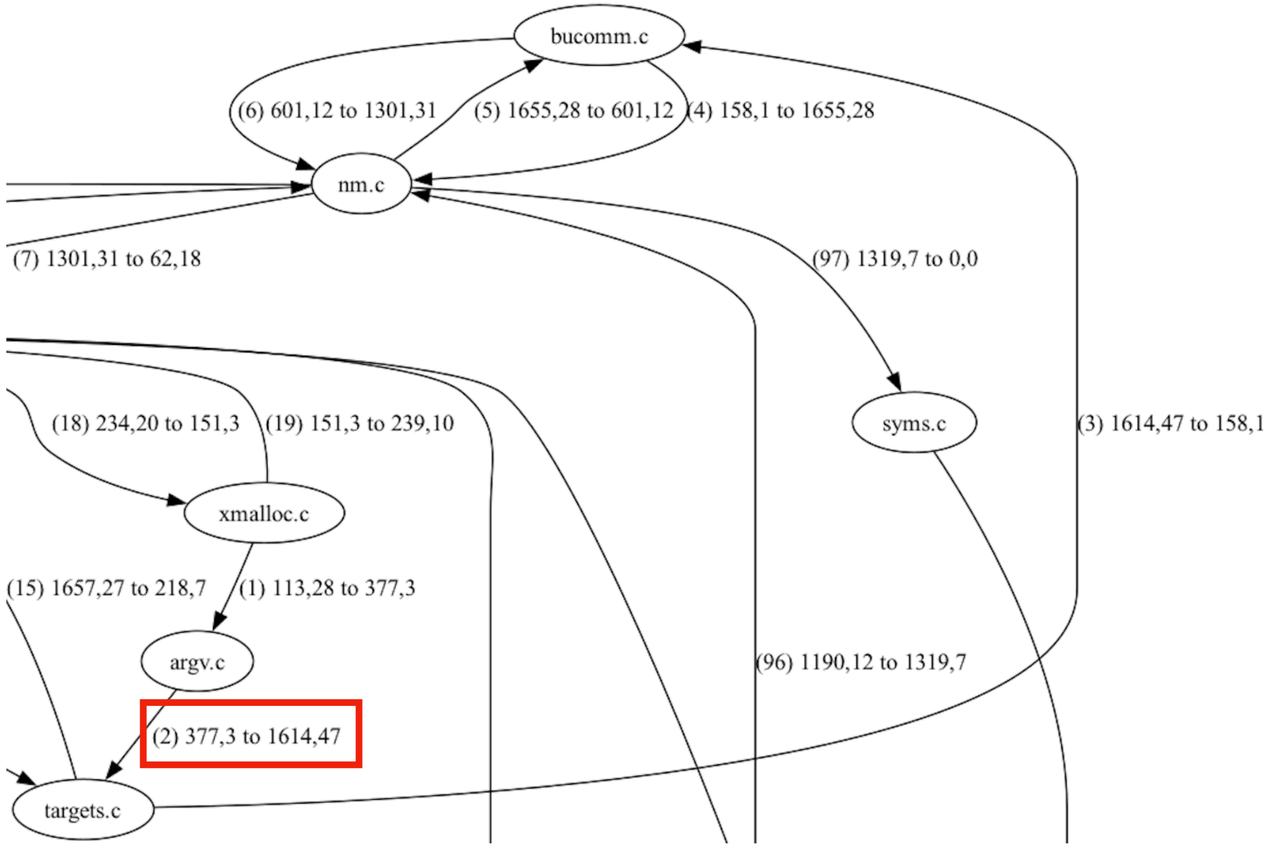

State transition diagram

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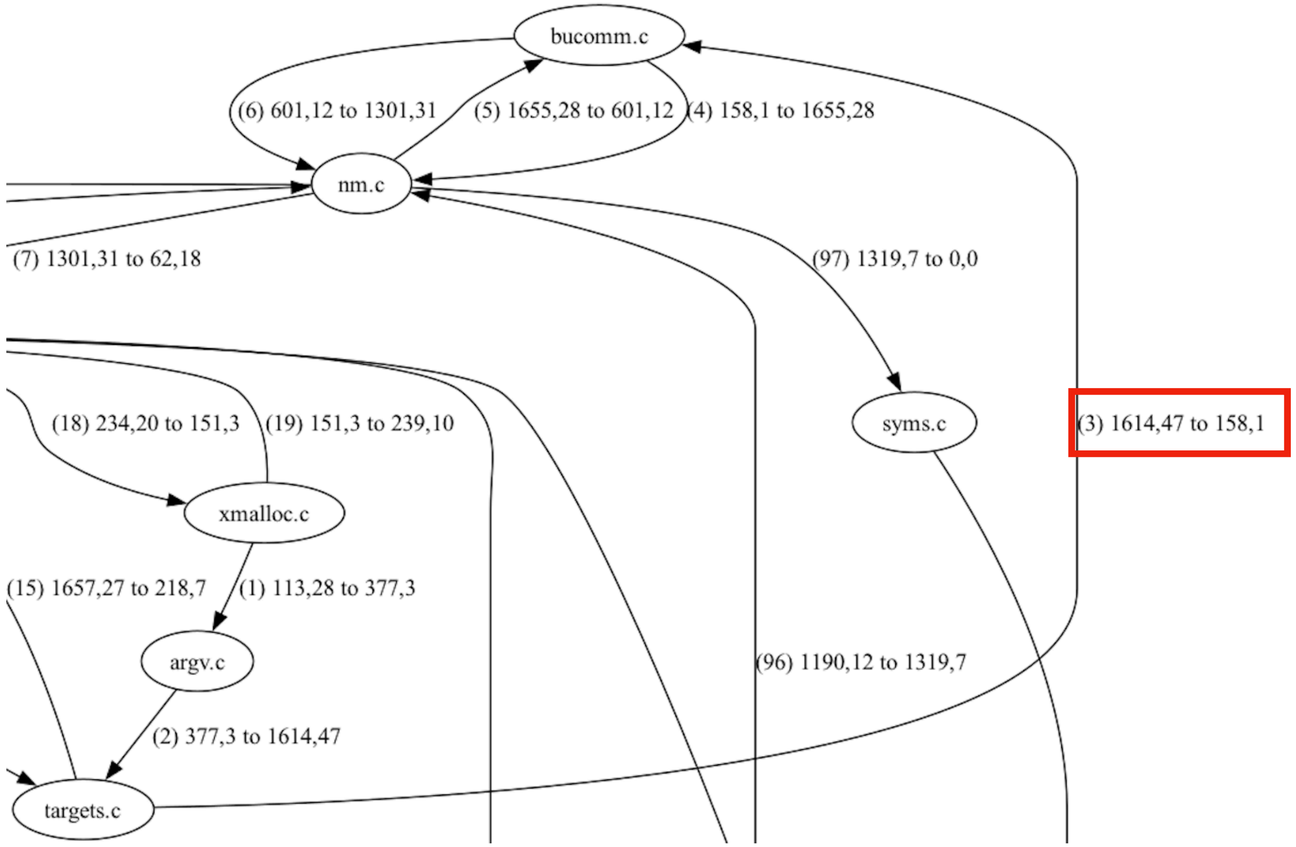

State transition diagram

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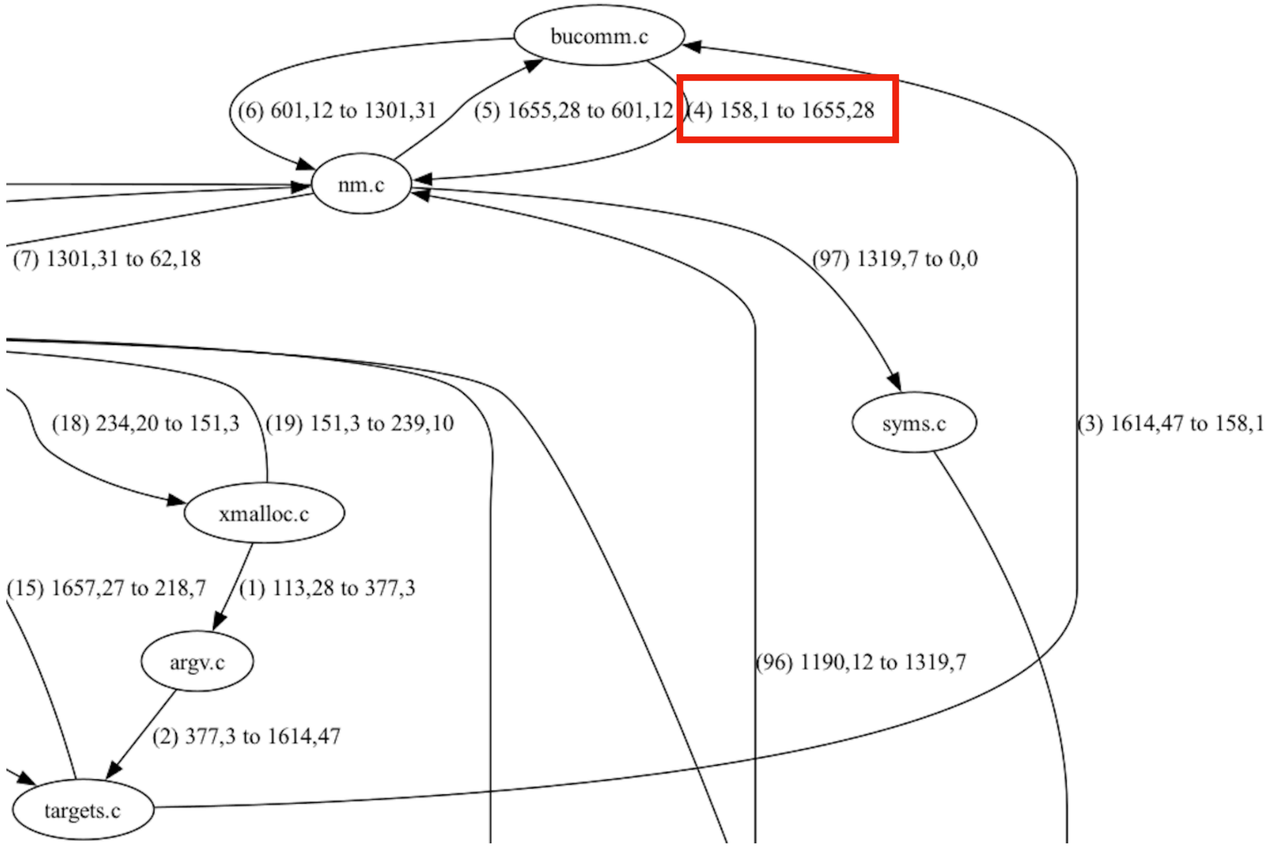
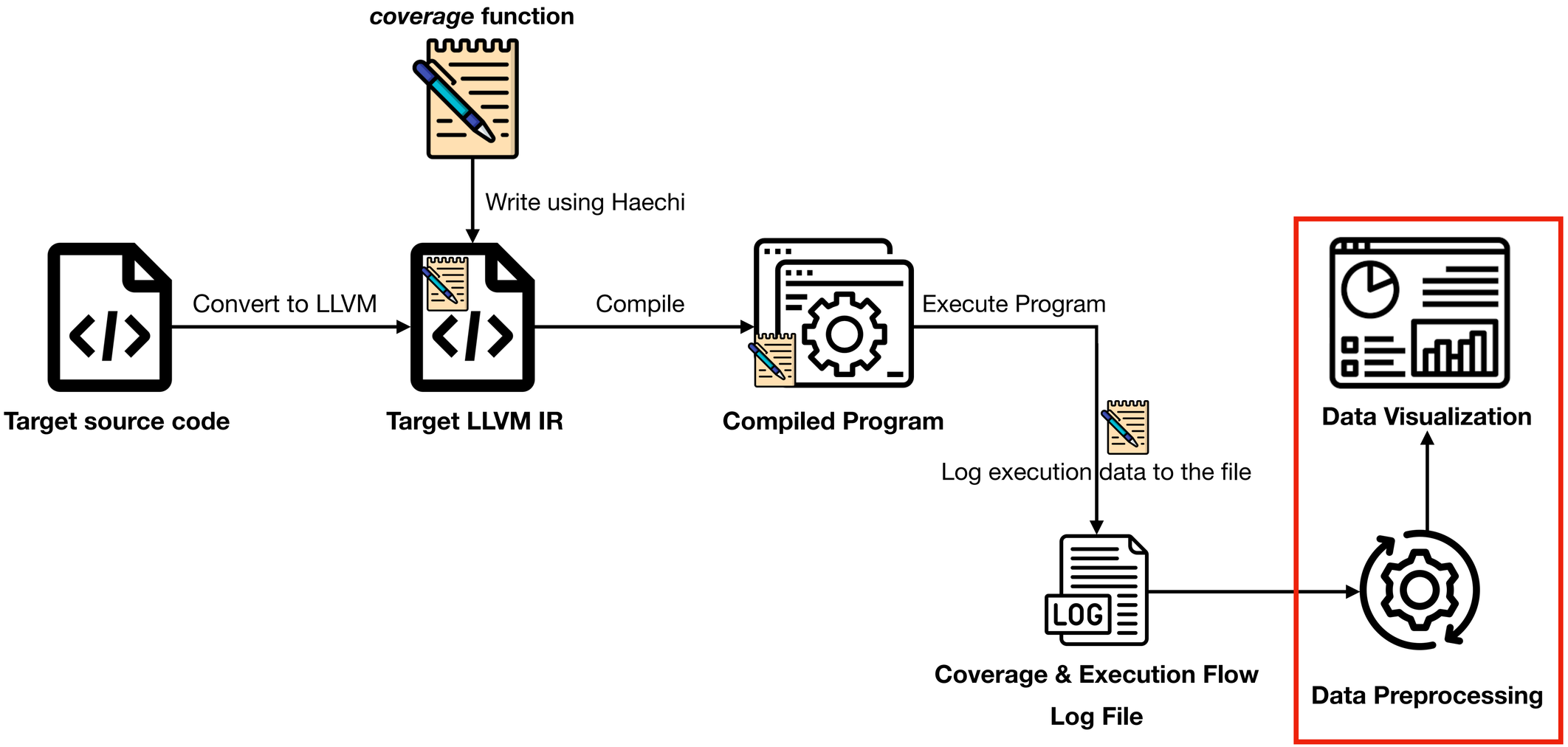


State transition diagram

Data Preprocessing

- I will demonstrate the data preprocessing in a video

Overview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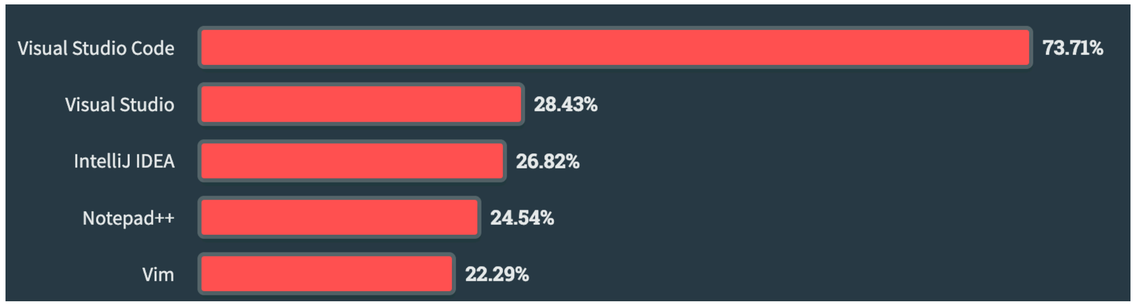
Data Visualization

- Visualize the .cov file obtained through the above process
- The visualization was implemented as a VSCode extension
- VSCode was chosen because it is used by the most developers[5]

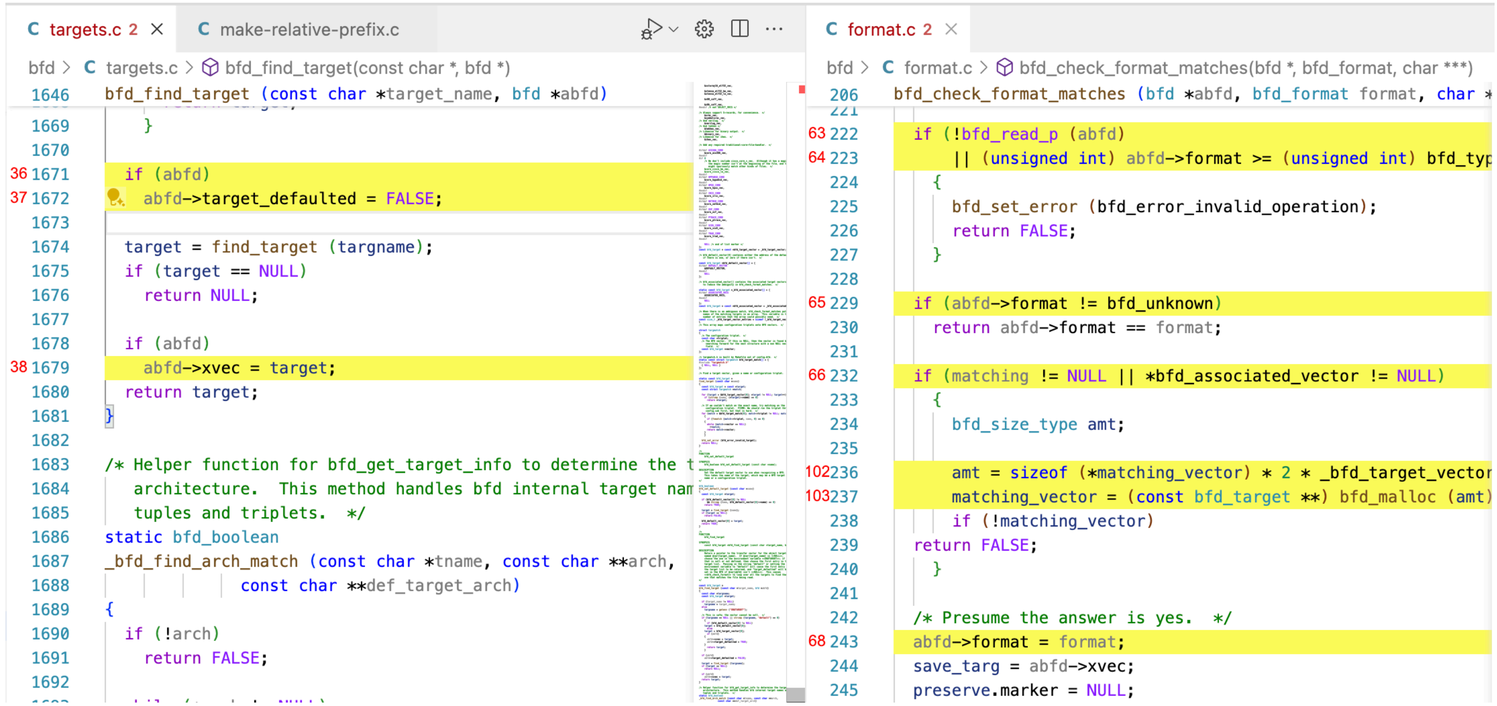


Visual Studio Code remains the preferred IDE across all developers

[5] Stack Overflow Survey 2023, "most popular technologies new collab tools", https://survey.stackoverflow.co/2023/#most-popular-technologies-new-collab-tools

Data Visualization

- Parse the .cov file and highlight the corresponding lines in the file
- Display the execution flow next to the line in red text



Data Visualization

- Since we're using VSCode, we can take advantage of its built-in shortcuts
  - F12 : Go to Definition
  - Cmd+U : Go to Last Cursor Position

Demo

- Let's trace CVE-2017-14940

Demo

- User can control *hdr->sh_info*

```
407 8196        contents = (bfd_byte *) bfd_malloc (hdr->sh_size);
    8197        if (contents == NULL)
    8198      goto error_return_verref;
    8199
408 8200        if (bfd_seek (abfd, hdr->sh_offset, SEEK_SET) != 0
409 8201        || bfd_bread (contents, hdr->sh_size, abfd) != hdr->sh_size)
    8202      goto error_return_verref;
    8203
    8204        elf_tdata (abfd)->verref = (Elf_Internal_Verneed *)
410 8205      bfd_zalloc2 (abfd, hdr->sh_info, sizeof (Elf_Internal_Verneed));
```

Demo

- User can control *hdr->sh_info*
- *hdr->sh_info* becomes *nmemb*
- Multiply *size* and *nmemb*
- Allocate as much as *size*

```
1026  bfd_zalloc2 (bfd *abfd, bfd_size_type nmemb, bfd_size_type size)
1027  {
1028    void *res;
1029
1030    if ((nmemb | size) >= HALF_BFD_SIZE_TYPE
1031        && size != 0
1032        && nmemb > ~(bfd_size_type) 0 / size)
1033      {
1034        bfd_set_error (bfd_error_no_memory);
1035        return NULL;
1036      }
1037
411 1038    size *= nmemb;
1039
1040    res = bfd_alloc (abfd, size);
1041    if (res)
1042      memset (res, 0, (size_t) size);
```

size can be a very large value

Demo

- User can control *hdr->sh_info*
- *hdr->sh_info* becomes *nmemb*
- Mult
- Allocate as much as *size*

```
root@c2617159fea5:/benchmark/RUNDIR-binutils-2.29/binutils-2.29# binutils/nm-new -A -a -l -S -s --special-
syms --synthetic --with-symbol-versions -D /benchmark/poc/nm/2017-14940
size: 250181845056
^C
```

```
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1032        && nmemb > ~(bfd_size_type) 0 / size)
1033      {
1039
1040    res = bfd_alloc (abfd, size);
1041    if (res)
1042      memset (res, 0, (size_t) size);
```

size can be a very large value

We can trace the bug with *CodeFlowVis*, without debug info

Evaluation

- RQ1. Is code coverage clearly provided according to the input?
- RQ2. Is the program execution flow clearly provided according to the input?

Evaluation

- RQ1. Is code coverage clearly provided according to the input?

```
1026  bfd_zalloc2 (bfd *abfd, bfd_size_type nmemb, bfd_size_type size)
1027  {
1028    void *res;
1029
1030    if ((nmemb | size) >= HALF_BFD_SIZE_TYPE
1031        && size != 0
1032        && nmemb > ~(bfd_size_type) 0 / size)
1033      {
1034        bfd_set_error (bfd_error_no_memory);
1035        return NULL;
1036      }
1037
411 1038   size *= nmemb;
1039
1040    res = bfd_alloc (abfd, size);
1041    if (res)
1042      memset (res, 0, (size_t) size);
```

Evaluation

- RQ1. Is code coverage clearly provided according to the input?

```
1026  bfd_zalloc2 (bfd *abfd, bfd_size_type nmemb, bfd_size_type size)
1027  {
1028    void *res;
1029
1030    if ((nmemb | size) >= HALF_BFD_SIZE_TYPE
1031        && size != 0
1032        && nmemb > ~(bfd_size_type) 0 / size)
1033      {
1034        bfd_set_error (bfd_error_no_memory);
1035        return NULL;
1036      }
1037
411 1038   size *= nmemb;
1039
1040    res = bfd_alloc (abfd, size);
1041    if (res)
1042      memset (res, 0, (size_t) size);
```

Even though it was run, it was not displayed.

Evaluation

- RQ2. Is the program execution flow clearly provided according to the input?

Evaluation

- RQ2. Is the program execution flow clearly provided according to the input?

```
READ of size 1 at 0x00000089fce4 thread T0
    #0 0x42f686 in strcmp /src/llvm-project/compiler-rt/lib/asan/../sanitizer_common/sanitizer_common_interceptors.inc:449:5
    #1 0x60f8e2 in _bfd_elf_get_reloc_section /benchmark/RUNDIR-binutils-2.28/binutils-2.28/bfd/elf.c:3562:10
    #2 0x613371 in assign_section_numbers /benchmark/RUNDIR-binutils-2.28/binutils-2.28/bfd/elf.c:3836:8
    #3 0x613371 in _bfd_elf_compute_section_file_positions /benchmark/RUNDIR-binutils-2.28/binutils-2.28/bfd/elf.c:4176:8
    #4 0x62bc26 in _bfd_elf_write_object_contents /benchmark/RUNDIR-binutils-2.28/binutils-2.28/bfd/elf.c:6222:12
    #5 0x5a060a in bfd_close /benchmark/RUNDIR-binutils-2.28/binutils-2.28/bfd/opncls.c:734:13
    #6 0x4d2276 in copy_file /benchmark/RUNDIR-binutils-2.28/binutils-2.28/binutils/objcopy.c:2886:51
    #7 0x4ce203 in copy_main /benchmark/RUNDIR-binutils-2.28/binutils-2.28/binutils/objcopy.c:4792:3
    #8 0x4c74ca in main /benchmark/RUNDIR-binutils-2.28/binutils-2.28/binutils/objcopy.c:4893:5
    #9 0x7f7d8fbdd082 in __libc_start_main /build/glibc-SzIz7B/glibc-2.31/csu/../csu/libc-start.c:308:16
    #10 0x41c57d in _start (/benchmark/bin/DAFL/objcopy-2017-8393+0x41c57d)
```

CVE-2017-8393

Evaluation

- RQ2. Is the program execution flow clearly provided according to the input?

```
READ of size 1 at 0x00000089fce4 thread T0
    #0 0x42f686 in strcmp /src/llvm-project/compiler-rt/lib/asan/../sanitizer_common/sanitizer_common_interceptors.inc:449:5
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    #10 0x41e57d in _start (/benchmark/bin/RAFL/objcopy-2017-8393+0x41c57d)
```

```
999  3547    type = elf_section_data (reloc_sec)->this_hdr.sh_type;
     3548    if (type != SHT_REL && type != SHT_RELA)
     3549      return NULL;
     3550
     3551    /* We look up the section the relocs apply to by name.  */
1000 3552    name = reloc_sec->name;
     3553    if (type == SHT_REL)
1001 3554      name += 4;
     3555    else
     3556      name += 5;
     3557
     3558    /* If a target needs .got.plt section, relocations in rela.plt/rel.plt
     3559       section apply to .got.plt section.  */
1002 3560    abfd = reloc_sec->owner;
     3561    if (get_elf_backend_data (abfd)->want_got_plt
1003 3562        && strcmp (name, ".plt") == 0)
```

Evaluation

- RQ2. Is the program execution flow clearly provided according to the input?

```
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    #0 0x42f686 in strcmp /src/llvm-project/compiler-rt/lib/asan/../sanitizer_common/sanitizer_common_interceptors.inc:449:5
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1003 3562        && strcmp (name, ".plt") == 0)
```

```
3868            if (elf_section_data (s)->this_hdr.sh_entsize == 0)
3869              elf_section_data (s)->this_hdr.sh_entsize
3870                = 4 + 2 * bfd_get_arch_size (abfd) / 8;
3871          }
```

Evaluation

- RQ2. Is the program execution flow clearly provided according to the input?

```
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    #4 0x62bc26 in _bfd_elf_write_object_contents /benchmark/RUNDIR-binutils-2.28/binutils-2.28/bfd/elf.c:6222:12
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```
3868            if (elf_section_data (s)->this_hdr.sh_entsize == 0)
3869              elf_section_data (s)->this_hdr.sh_entsize
3870                = 4 + 2 * bfd_get_arch_size (abfd) / 8;
3871          }
```

```
862 4161  if (bed->elf_backend_begin_write_processing)
    4162    (*bed->elf_backend_begin_write_processing) (abfd, link_info);
    4163
863 4164  if (! prep_headers (abfd))
    4165    return FALSE;
    4166
    4167  /* Post process the headers if necessary.  */
896 4168  (*bed->elf_backend_post_process_headers) (abfd, link_info);
    4169
    4170  fsargs.failed = FALSE;
    4171  fsargs.link_info = link_info;
    4172  bfd_map_over_sections (abfd, elf_fake_sections, &fsargs);
    4173  if (fsargs.failed)
    4174    return FALSE;
    4175
942 4176  if (!assign_section_numbers (abfd, link_info))
    4177    return FALSE;
    4178
    4179  /* The backend linker builds symbol table information itself.  */
1009 4180  need_symtab = (link_info == NULL
1010 4181         && (bfd_get_symcount (abfd) > 0
1011 4182             || ((abfd->flags & (EXEC_P | DYNAMIC | HAS_RELOC))
    4183                 == HAS_RELOC)));
```

Evaluation

- RQ2. Is the program execution flow clearly provided according to the input?

It does not display **100%** of both code coverage and execution flow

However, it provides **enough information** to trace bugs effectively

Future Work

- Make the state transition diagram interactive
- It does not provide complete code coverage information
  - Some lines are not displayed during the C ↔ LLVM conversion process
  - Combine with GCOV

Summary

- Coverage alone makes it **difficult** to understand the **execution flow**
  - Tracing becomes challenging when a bug occurs
- To address these issues, we propose the **CodeFlowVis** visualizer
- It stores coverage and execution flow information based on LLVM
- It visualizes this information to facilitate **efficient debugging**
- We have **successfully traced real bugs** using this tool