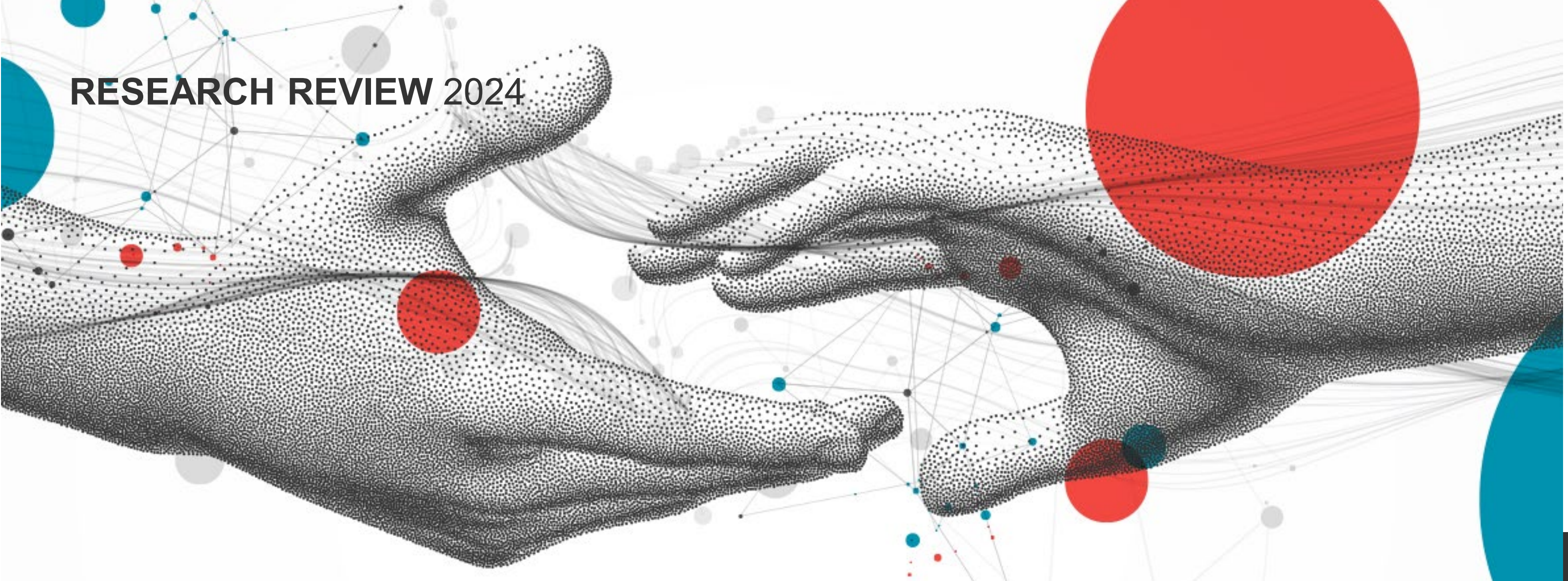
RESEARCH REVIEW 2024



Carnegie Mellon University
Software Engineering Institute

Detection of Malicious Code Using Information Flow Analysis

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Document Markings

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Problem

- Department of Defense (DoD) software supply chains
- Example incidents:
  - `xz` backdoor incident of 2024
  - SolarWinds incident of 2020: infected 18,000 organizations, 100 of which were then targeted
- Our tool detects two types of malicious code:
  1. Exfiltration of sensitive information
  2. Timebombs/logic bombs, remote-access Trojans (RATs), etc.
- We call our tool “DMC” (short for “Detection of Malicious Code”).
  - `https://github.com/cmu-sei/dmc`
- Project status: Began October 2022, ending November 2024

Our Approach (1)

- Our tool flags code as **potentially** malicious.
- It detects "business logic" vulnerabilities (such as Log4Shell in Log4j) too.
- Out of scope: Undefined behavior (e.g., buffer overflows)
- **Goal for our tool:** concise and precise output → quick and accurate human adjudication

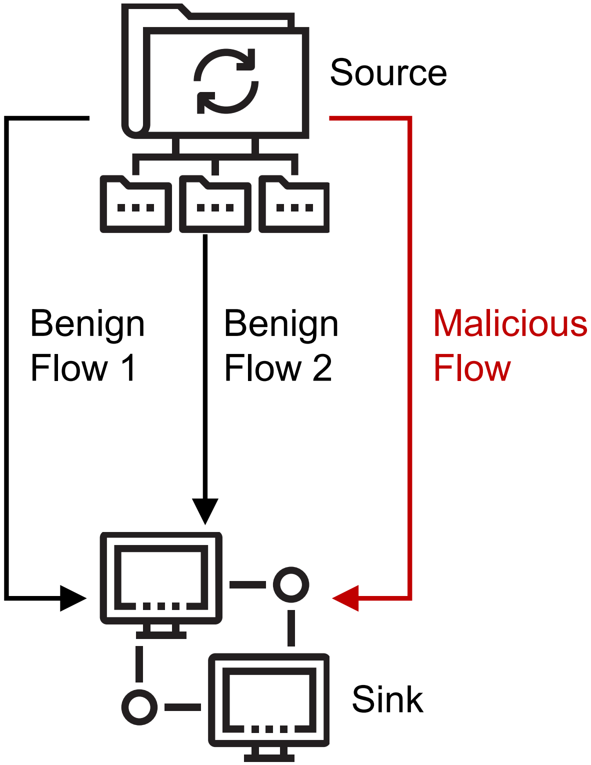
Our Approach (2)

- We are using only static analysis, not dynamic analysis.
- So far, we have focused on C/C++ codebases.
- Our tool works natively on LLVM intermediate representation (IR).
  - LLVM is a compiler infrastructure project.
  - The name “LLVM” originally stood for “Low Level Virtual Machine.”
- We have some support for binaries by lifting to LLVM IR.
- We can also fairly easily support other languages that compile to LLVM IR.

PhASAR

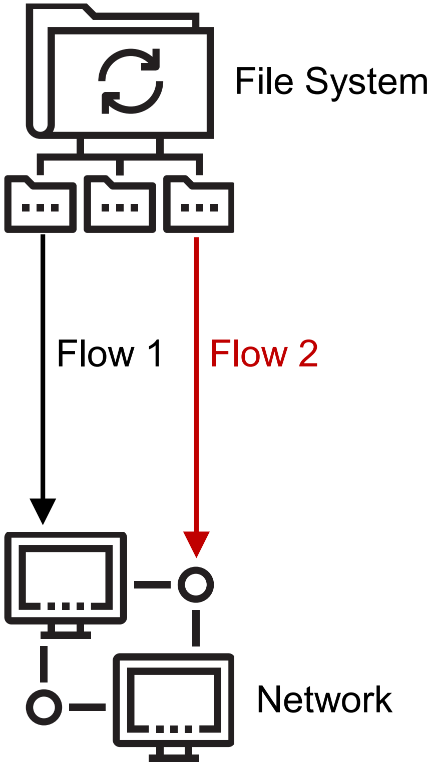
- Initially, we built on PhASAR, which is a static-analysis framework based on LLVM.
- Unfortunately, PhASAR ended up having trouble as we scaled to real-world codebases:
  - Took 15 minutes to analyze `dos2unix` (a very small program, approx. 4,000 lines of code)
  - Ran out of memory (with 24 GB of RAM) on `git`
  - Attempts to simplify the analysis (to speed it up and reduce memory usage) were unfruitful
  - Global variables were always aliased with function parameters, producing many false positives
- Abandoned PhASAR, reimplemented taint analysis from scratch, building only on LLVM
  - We improved scalability by avoiding construction of the supergraph used in PhASAR’s Interprocedural Finite Distributive Subset (IFDS) analysis, at the cost of less context sensitivity.
  - Much faster and less memory-intensive; can analyze `git` (approx. 275,000 lines of code) in just a few minutes with memory usage under 15% on a virtual machine (VM) with 8 GB of RAM
  - Current limitations: Only handles C (with incomplete support for C++), limited alias analysis, limited analysis on function pointers, etc.

Information Flow Analysis



- Static taint analysis to track flow of sensitive data
  - Successful track record (e.g., finding malicious flows of information in Android apps)
  - *Sources* are designated system application programming interface (API) calls that return potentially sensitive information.
  - *Sinks* are designated system API calls that can be used to exfiltrate information to outside the program.
- **Limitation:** Conflates together all flow paths from a given source to a given sink. So, a malicious flow path can be "hidden" by a benign flow path.
- **Our idea:** Separate the flows by features relevant to detection of malicious code

Motivating Example E1 (Pseudocode)



```
function Flow_1() {
  cmd = read_from_keyboard();
  if (is_upload_cmd(cmd)) {
    name = get_file_name(cmd);
    x = read_from_file(name);
    send_to_network(x);
  }
}

function Flow_2() {
  data = read_from_network();
  if (is_special_cmd(data)) {
    x = read_from_file("secrets.txt");
    send_to_network(x);
  }
}
```

Idea for Ideal Output

Example of Ideal Output

- Flow 1:
  - Source: File system
    - Filename is specified by user.
  - Sink: Network
    - IP: 127.0.0.1
    - Port: 12345

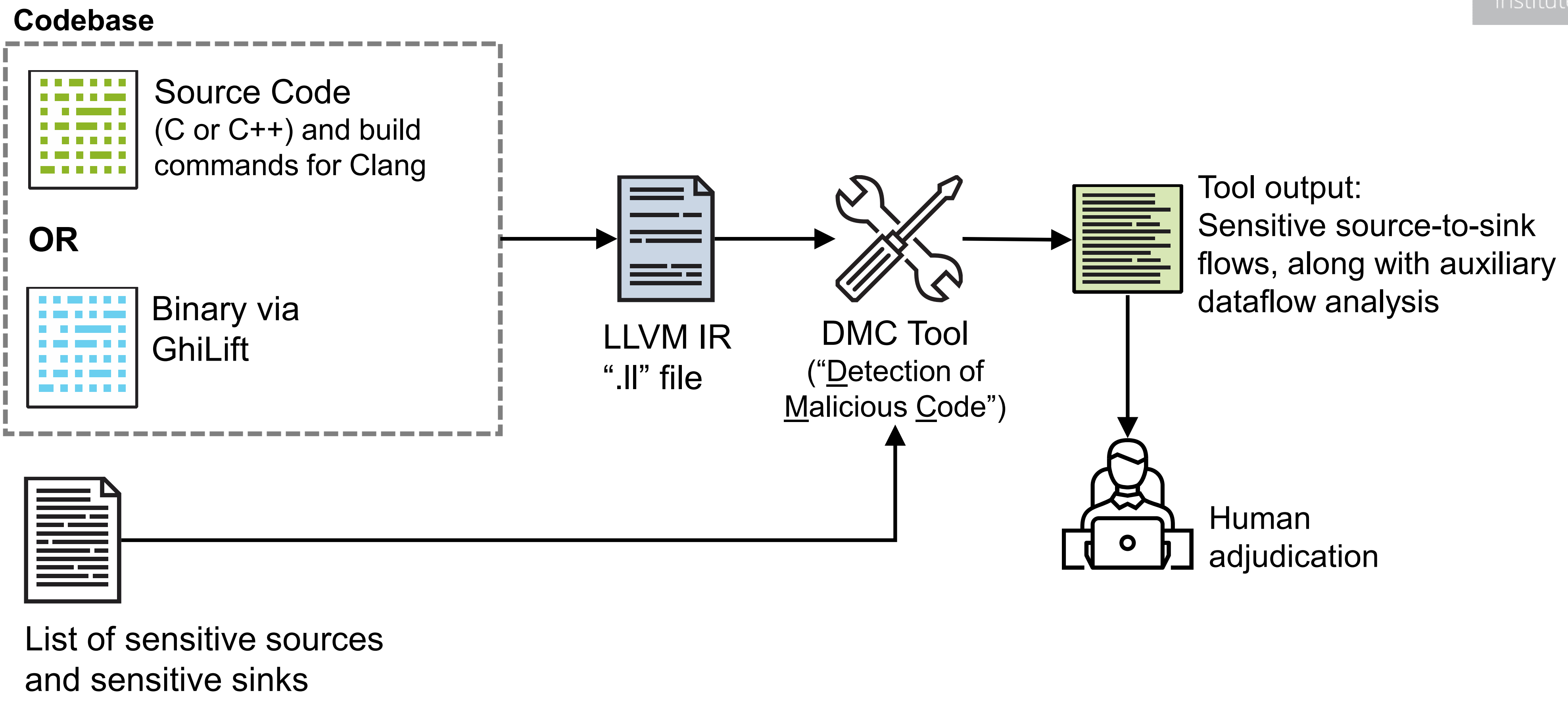
- Flow 2:
  - Source: File system
    - Filename is hardcoded **`secrets.txt`**.
  - Sink: Network
    - IP: 127.0.0.1
    - Port: 12345

Example E1:

```
function Flow_1() {
  cmd = read_from_keyboard();
  if (is_upload_cmd(cmd)) {
    name = get_file_name(cmd);
    x = read_from_file(name);
    send_to_network(x);
  }
}

function Flow_2() {
  data = read_from_network();
  if (is_special_cmd(data)) {
    x = read_from_file("secrets.txt");
    send_to_network(x);
  }
}
```

Diagram of Our Tool with Its Input and Output



Codebase

Source Code
(C or C++) and build
commands for Clang

OR

Binary via
GhiLift

LLVM IR
".ll" file

DMC Tool
("Detection of
Malicious Code")

Tool output:
Sensitive source-to-sink
flows, along with auxiliary
dataflow analysis

Human
adjudication

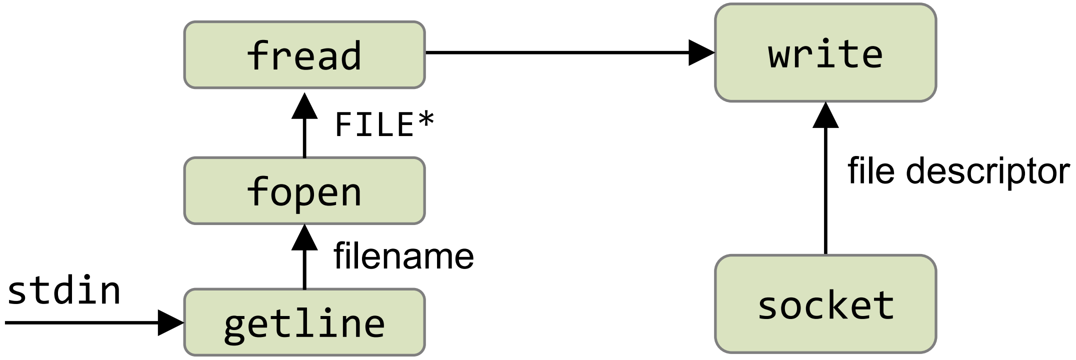
List of sensitive sources
and sensitive sinks

Creating the List of Sources and Sinks

- For well-known functions exported by the operating system and libraries, we used a large language model (LLM), specifically GPT-4, to identify:
  - whether the return value is a source
  - which parameters are sinks
  - which parameters are sources
    - A parameter is a source if it is a pointer to a buffer that the API call fills with potentially sensitive data.
- GPT-4 knows common Windows and Linux API functions. For lesser-known operating systems, the LLM may need a description of the function (e.g., the `man` page).
- Two methods of generating the list of sources and sinks:
  1. Do up-front analysis of system API functions and/or
  2. Run our tool on the program:
     a. The tool’s output will indicate which external functions it doesn’t recognize.
     b. Feed those function names to the LLM.

Simple Example (mal-client-3.c)

```
[
{"sink": {"func":"write", "callsite":["mal-client-3.c","main",152,21],
    "aux file": [{"func":"socket", "callsite":["mal-client-3.c","main",65,18]}]},
 "srcs": [{"func":"fread", "callsite":["mal-client-3.c","main",139,29],
    "aux file": [{"func":"fopen", "callsite":["mal-client-3.c","main",132,26],
      "aux file": [{"func":"getline", "callsite":["mal-client-3.c","main",106,26], "FILE*":"stdin"},
                   {"func":"getline", "callsite":["mal-client-3.c","main",117,30], "FILE*":"stdin"}]}]}]},
...
]
```



Simple Example (mal-client-3.c)

```
[
{"sink": {"func":"write", "callsite":["mal-client-3.c","main",152,21],
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      "aux file": [{"func":"getline", "callsite":["mal-client-3.c","main",106,26], "FILE*":"stdin"},
                   {"func":"getline", "callsite":["mal-client-3.c","main",117,30], "FILE*":"stdin"}]}]}]},

{"sink": {"func":"write", "callsite":["mal-client-3.c","main",158,17],
    "aux file": [{"func":"socket", "callsite":["mal-client-3.c","main",65,18]}]},
 "srcs": [{"func":"getline", "callsite":["mal-client-3.c","main",106,26], "FILE*":"stdin"},
          {"func":"getline", "callsite":["mal-client-3.c","main",117,30], "FILE*":"stdin"}]},

{"sink": {"func":"write", "callsite":["mal-client-3.c","main",194,29],
    "aux file": [{"func":"socket", "callsite":["mal-client-3.c","main",65,18]}]},
 "srcs": [{"func":"fread", "callsite":["mal-client-3.c","main",180,37],
    "aux file": [{"func":"fopen", "callsite":["mal-client-3.c","main",173,34],
      "aux file": [{"filename":"secrets.txt"} ]}]}]}
]
```
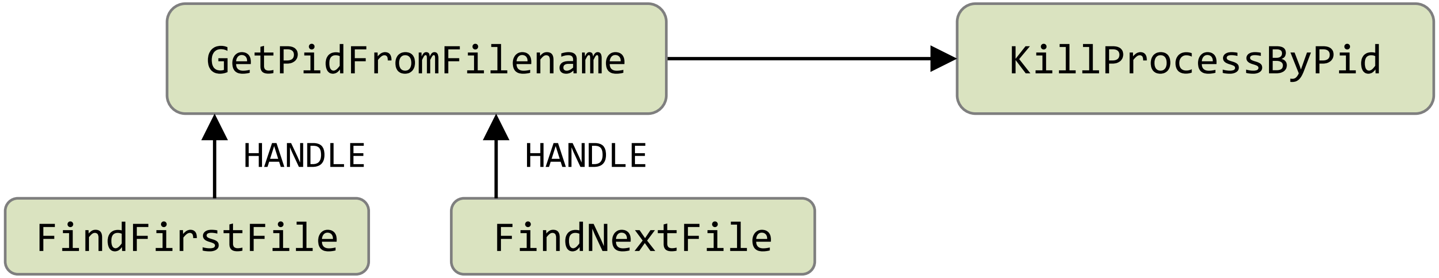
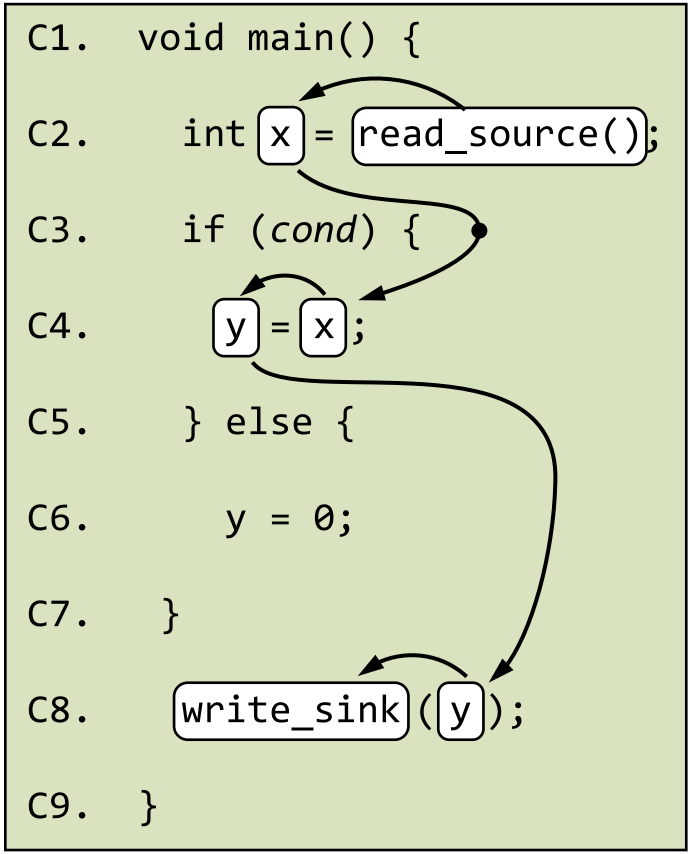

Real-World Example: Athena Malware

- Available at: `https://github.com/ytisf/theZoo`
- One malicious action we can detect is finding and terminating other bots.
- `Botkiller.cpp`, function `ScanDirectoryForBots`
- Detected flow:



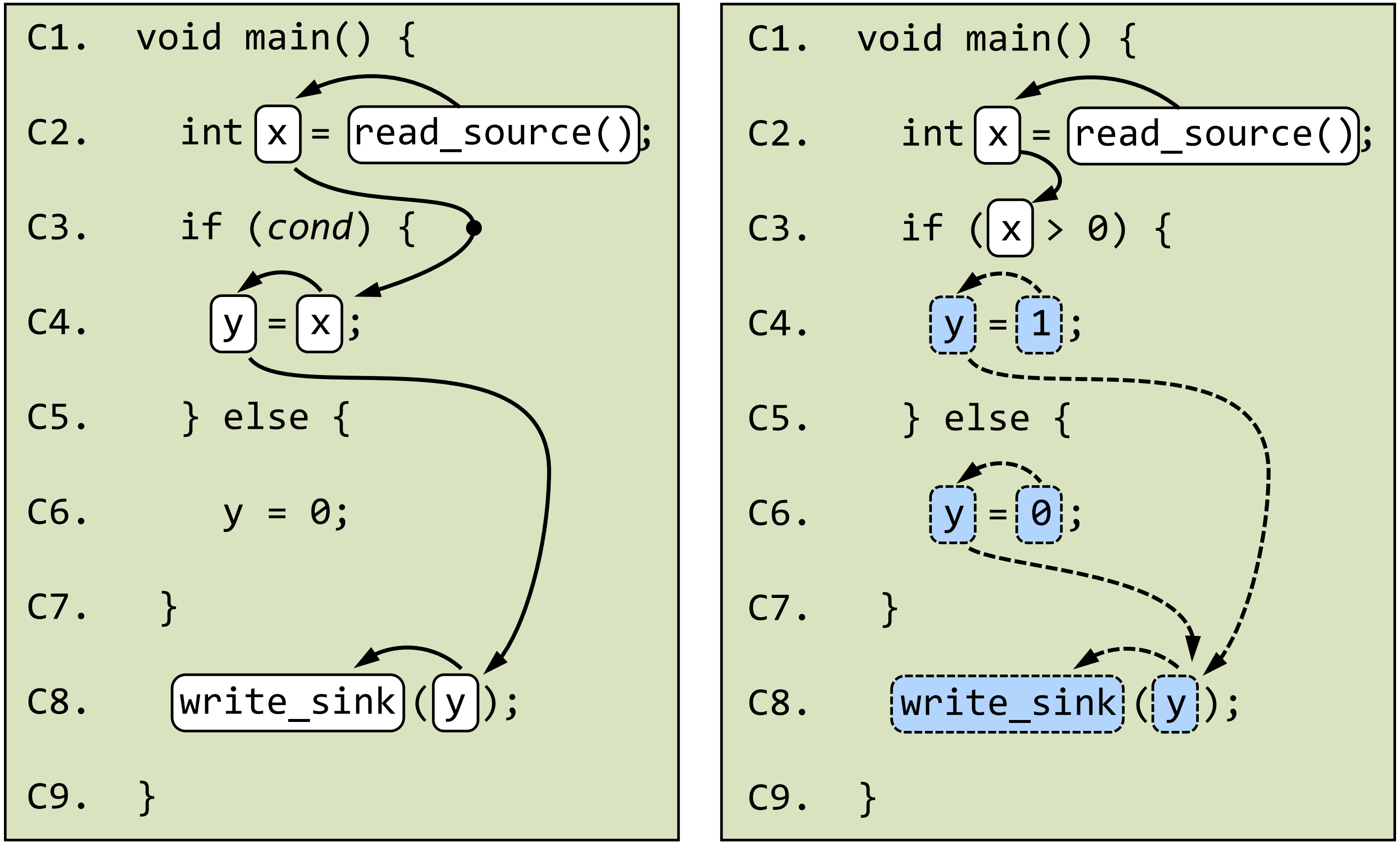
Flow Paths



```
C1.  void main() {
C2.    int x = read_source();
C3.    if (cond) {
C4.      y = x;
C5.    } else {
C6.      y = 0;
C7.   }
C8.    write_sink(y);
C9.  }
```

- A *flow path* describes a flow of information in a single run of the program.
- The arrows in the diagram at the right illustrate a flow path from `read_source` to `write_sink`.
  - For each arrow, there is a direct flow from the origin of the arrow to the target of the arrow.
  - The arrows follow along a *trace* (i.e., the sequence of instructions executed in a run of the program).

Explicit Flow vs. Implicit Flow



```
void main() {
   int x = read_source();
   if (cond) {
     y = x;
   } else {
     y = 0;
   }
  write_sink(y);
}
```

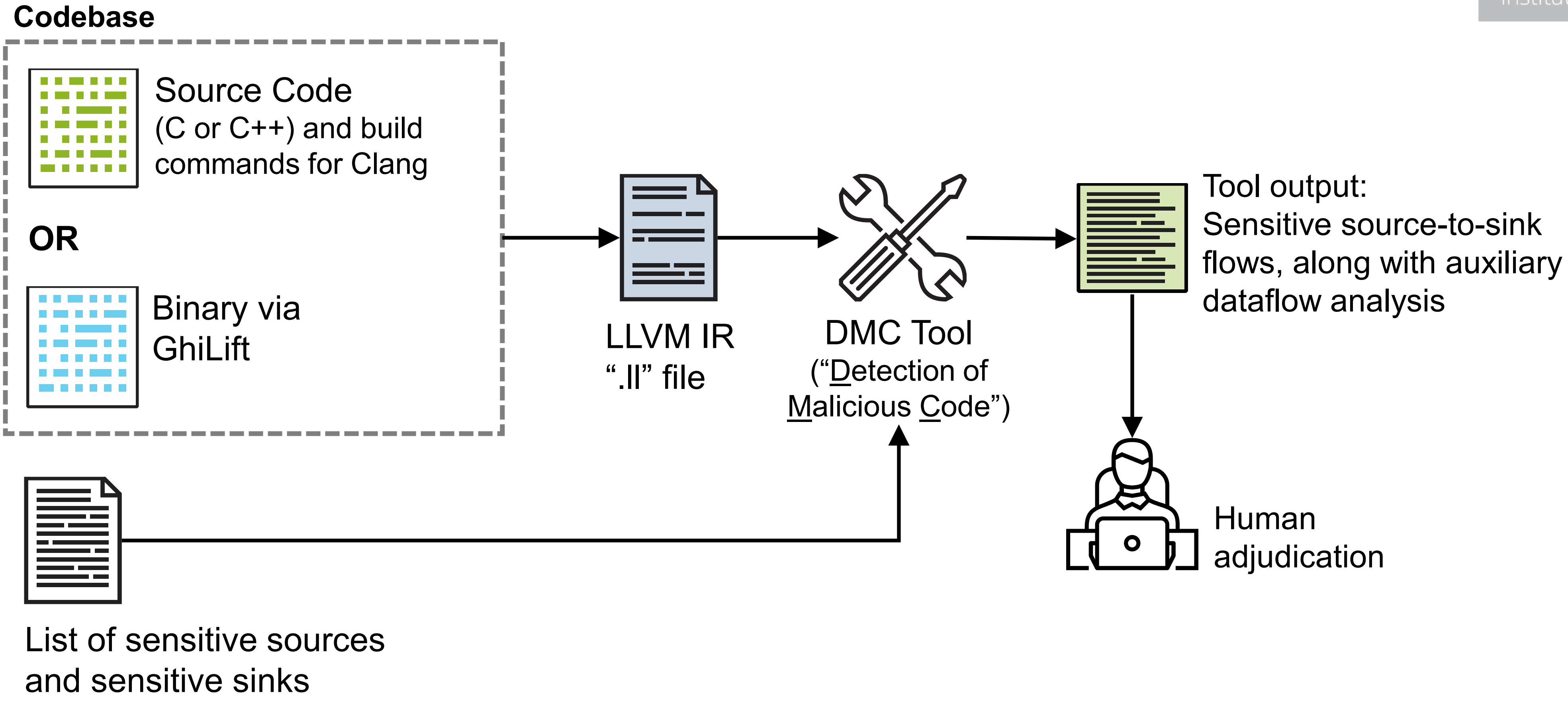
```
void main() {
   int x = read_source();
   if (x > 0) {
     y = 1;
   } else {
     y = 0;
   }
  write_sink(y);
}
```

An *implicit flow* doesn't have a flow path from source to sink; rather, the source influences the sink indirectly via a branch condition.

We do not consider implicit flows in this project.

- Techniques for implicit flows generally introduce an excessive amount of false alarms.
- However, there are heuristics that can be used to try to identify laundering of data through an implicit flow.

Recap: Diagram of Our Tool with Its Input and Output



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Conclusion and Team

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Our tool detects potentially malicious code by tracing the flow of sensitive information and auxiliary information.

Contact: info@sei.cmu.edu

Tool available at:
https://github.com/cmu-sei/dmc

This release includes the source code, a Docker file, tests, documentation, and a demo.

We'd appreciate any feedback if you try out the tool!