Detecting vulnerabilities in source code with AI

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Goal of this talk…

- Give brief overview of our work
- Discover possibility for synergy/cooperation

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Introduction

- How to detect/discover vulnerabilities in software?

- DAST: dynamic analysis (execution of binary)
  - vulnerability scanners
  - fuzz testing

- SAST: static analysis (of source code)
  - type checking (for information-flow analysis)
  - static code analysis (Coverity, Fortify, PreFAST, …)

    → rule-based analysis using control/data flow analysis
  - *applying AI*

    → *learning from code properties*

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Vulnerability detection with AI

- Analyse meta-information, ie. metrics derived from
  - source code (complexity, size)
  - code repositories (churn, age, comments)
  - developers (developer activity, fault history)

Very modest results
- applicable only for mature software systems
- unable to distinguish vulnerabilities from defects

- Analyse program code (syntax and/or semantics)
  - anomaly detection (look for patterns that do not conform to normal/expected behaviour)
  - vulnerable code pattern recognition (look for patterns that relate to abnormal behaviour)

Eg. Software Vulnerability Analysis and Discovery Using Machine-Learning and Data-Mining Techniques: A Survey
Seyed Mohammad Ghaffarian and Hamid Reza Shahriari, ACM Computing Surveys, Vol. 50, No. 4, Article 56, August 2017.

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Lots of research opportunities

- Method
  - approach (analyse meta-information, program syntax/semantics, hybrid, combi SAST/DAST, …)
  - AI technique (rule-based, machine learning, deep learning)
  - type of application and programming language (web applications in PHP and JavaScript, embedded software in C/C++, general applications in Java or C#, …)
  - type of vulnerabilities (code injection, buffer overflow, …)

- Questions
  - How good is it for detecting vulnerabilities?
  - How does it compare to other methods?
  - How does it make decisions (explainable)?
  - How specific/general is it?
  - How can it be applied in practice?

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Our (ongoing) research

- Team: Arjen Hommersom, Harald Vranken, master students
  - Discovering XSS and SQLi vulnerabilities in PHP code, using machine learning (Jorrit Kronjee, 2018) and deep learning (Bart Elema, 2020)
  - Discovering path traversal and SQLi/XMLi vulnerabilities in C# code, using code2vec (Mathijssen, 2022)
  - Discovering memory corruption vulnerabilities in C++ code, using graph neural networks (De Kraker, 2022) and layerwise relevance propagation (Foeken, 2022)

- Publications
  - Kronjee, Hommersom & Vranken: *Discovering software vulnerabilities using data-flow analysis and machine learning* (ARES 2018)
  - De Kraker, Vranken & Hommersom: *GLICE: Combining Graph Neural Networks and Program Slicing to Improve Software Vulnerability Detection* (DevSecOpsRO 2023)

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Our research method

1. Create dataset of code samples (both vulnerable and non-vulnerable samples)
   - challenge: how to obtain samples?

2. Translate code into some abstract representation (graph/model)
   - challenge: how to preserve properties that identify vulnerabilities?

3. Transform graph/model into feature vectors
   - challenge: ML (with feature engineering) or DL?

4. Train a classifier
   - challenge: what ML/DL model?

5. Evaluate trained classifier
   - challenge: how to explain false classifications, and how to improve the model?

Approach
- Apply domain knowledge (ie. security)
- Consider AI methods ‘as is’ (toolbox)

→ primarily security research (applied AI research)

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Case studies

1. Discovering XSS and SQLi vulnerabilities in PHP code using machine learning
   Kronjee, Hommersom &Vranken: *Discovering software vulnerabilities using data-flow analysis and machine learning*
   (ARES 2018)

2. Discovering memory corruption vulnerabilities in C++ code using graph neural networks
   De Kraker, Vranken & Hommersom: *GLICE: Combining Graph Neural Networks and Program Slicing to Improve Software Vulnerability Detection*
   (DevSecOpsRO 2023)

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Discovering XSS and SQLi vulnerabilities in PHP code

- Inspired by prior work of Fabian Yamaguchi and Konrad Rieck (and others) in Germany and Lwin Khin Shar and Hee Beng Kuan Tan (and others) in Singapore

- Approach
  1. Extract features from PHP source code samples using data-flow analysis
  2. Feature selection and supervised machine learning to train various classifiers
  3. Perform experiments to evaluate how good it is

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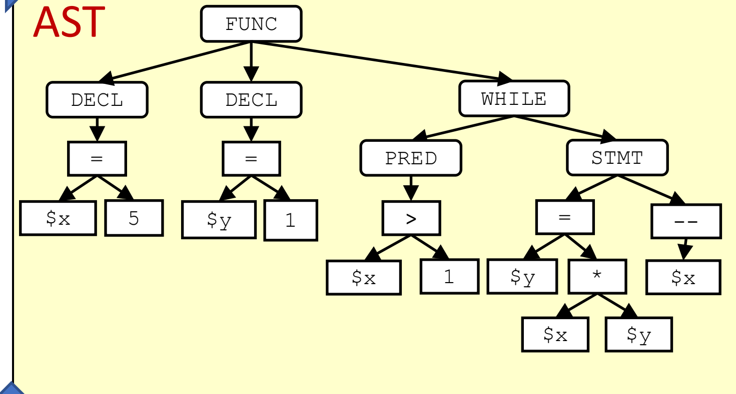
Data-flow analysis

- Create AST from source code
- Derive CFG from AST
- Determine reaching definitions and use-definitions chains
  - Definition (assignment) on line *i* reaches to line *j* if the variable in *i* can reach *j* without intervening definitions
  - UD chain for use of a variable lists all definitions of that variable that can reach that use without any other intervening definitions

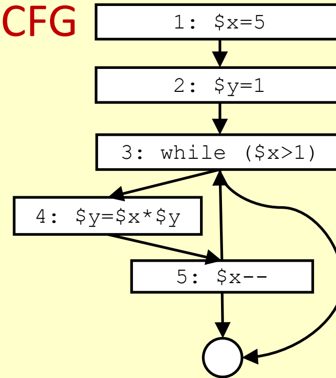
Source code

```
$x = 5;
$y = 1;
while ($x > 1) {
    $y = $x * $y;
    $x--;
}
```

AST



CFG



Reaching definitions

Line	IN	GEN	OUT	KILL
1	∅	x1	x1	x5
2	x1	y2	x1,y2	y4
3	x1,x5,y2,y4	∅	x1,x5,y2,y4	∅
4	x1,x5,y2,y4	y4	x1,x5,y4	y2
5	x1,x5,y4	x5	x5,y4	x1

Use-definition chains

Use	UD chain
y4	y2,y4
x5	x1,x5

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Extracting features

- General pattern with XSS and SQLi
  - tainted data enters application
  - application does not sufficiently validate and sanitise the data
  - application uses the data in a vulnerable function
- Tainted data
  - assume all variables are tainted (except variables of type *float*, *int*, *double, bool*)
  - feature: consider line of code as tainted if at least one variable on the line is tainted
- Sanitisation
  - PHP function `filter_var()` uses constant as second parameter to specify type of filtering
  - features: use of these constants (like `FILTER_SANITIZE_STRING`)
- Potentially vulnerable functions
  - features: function usage (also consider UD chain for data used in function)

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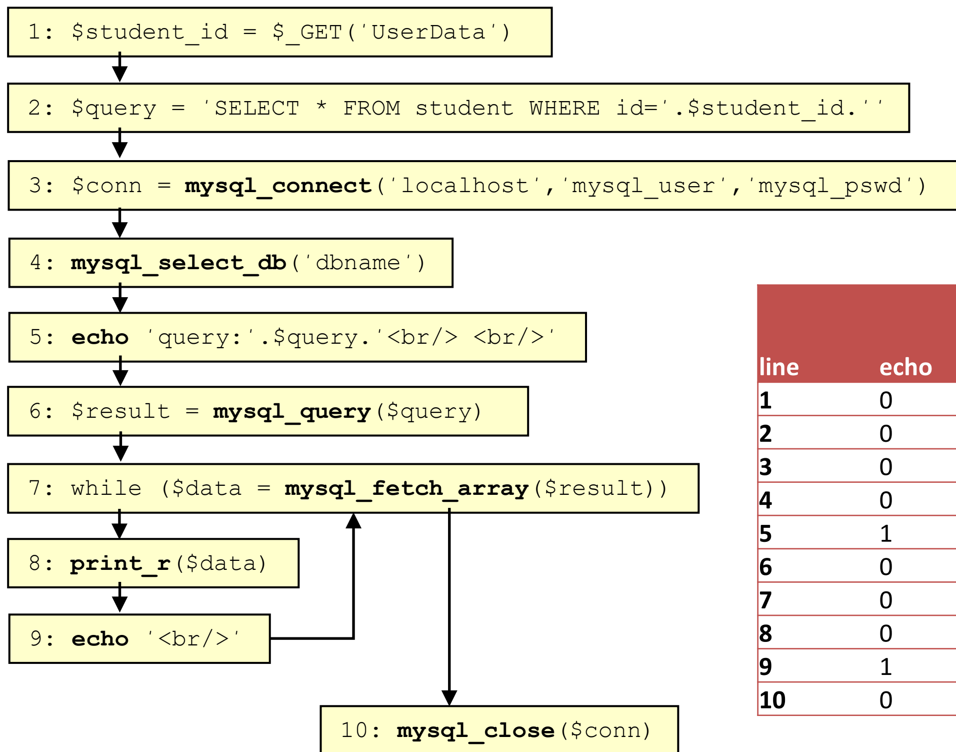
Example



use	UD chain
...	...
$result7	$result6
$data8	$data7
...	...

line	echo	mysql_ close	mysql_ connect	mysql_ fetch_ array	mysql_ query	...	tainted	vulnerable
1	0	0	0	0	0	...	1	0
2	0	0	0	0	0	...	1	0
3	0	0	1	0	0	...	0	0
4	0	0	0	0	0	...	0	0
5	1	0	0	0	0	...	1	0
6	0	0	0	0	1	...	1	1
7	0	0	0	1	1	...	1	1
8	0	0	0	1	0	...	1	1
9	1	0	0	0	0	...	0	0
10	0	1	1	0	0	...	0	0

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Results

- Created dataset of PHP code samples (from NIST NVD and SAMATE) with XSS or SQLi vulnerabilities
- Trained 5 ML classifiers (Random forest, Decision tree, …) separately for SQLi and XSS
- Evaluated classifiers
  - standard metrics
  - comparison against other open-source tools
  - try on PHP code repositories (identified SQLi in Piwigo, CVE-2018-6883)

SQLi

	AUC-PR
Decision Tree	**0.88**
Logistic Regression	0.87
Random Forest	0.85
TAN	0.75
Naive Bayes	0.64
Dummy	0.51

	Precision	Recall	F_1-score
Our tool	**0.94**	**0.94**	**0.94**
Pixy	0.86	0.61	0.69
RIPS	0.83	0.80	0.82
WAP	0.83	0.84	0.83
Yasca	0.01	0.10	0.02

XSS

	AUC-PR
Decision Tree	**0.82**
Random Forest	**0.82**
TAN	0.81
Logistic Regression	0.79
Naive Bayes	0.69
Dummy	0.51

	Precision	Recall	F_1-score
Our tool	**0.79**	**0.71**	**0.71**
Pixy	0.61	0.61	0.61
RIPS	0.37	0.61	0.46
WAP	0.51	0.58	0.51
Yasca	0.24	0.25	0.24

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Case studies

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Discovering buffer overflows in C++ code

- Inspired by prior work of Chinese researchers at Huazhong University of Science and Technology (SySeVR, VulDeepecker) and Northwest University (FUNDED)

- Approach
  1. Apply program slicing
     - program slice contains all statements on which arguments of a function call depend
     - similar to SySeVR, but consider call tree of multiple functions instead of single function
  2. Transform program slide into Graph Neural Network (GNN)
     - similar to FUNDED, but with support for more language constructs and bug fixes
  3. Train classifier (GLICE)
  4. Perform experiments to evaluate how good it is

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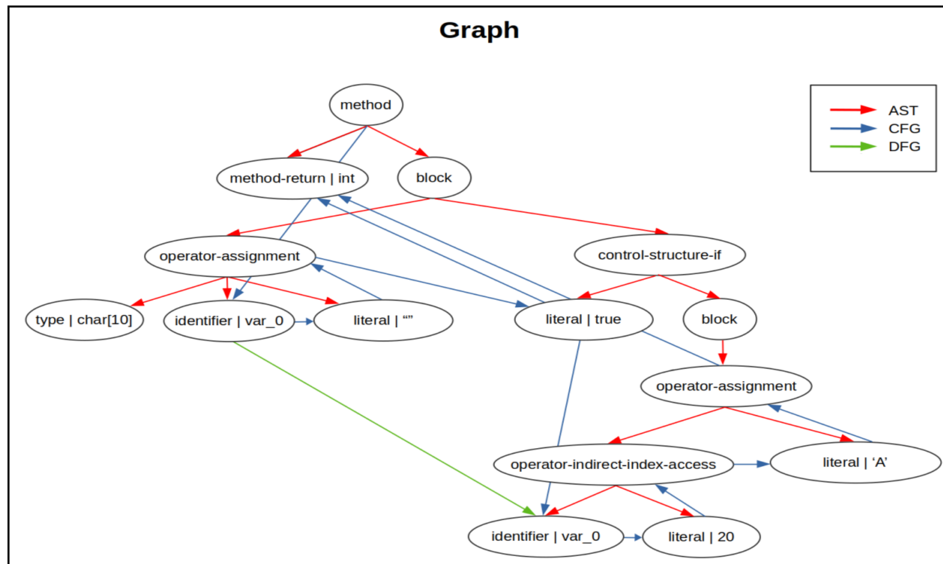
Example

Code sample with vulnerability at line 4:

```
1    void Print_Prefix(char* source)
2    {
3        char dest[5]="A";
4        strcat(dest, source);
5        printf("%s\n", dest);
6    }
7
8    int main()}
9    {
10       char source[10]="";
11       memset(source, 'B', 9);
12       source[9]="\0";
13       Print_Prefix(source);
14   }
```

Program slice for criterion (strcat(), {dest, source}):

```
10   char source[10]="";
11   memset(source, 'B', 9);
12   source[9]="\0";
 3   char dest[5]="A";
 4   strcat(dest, source);
```



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Results

- Created dataset of C++ code samples (from NIST NVD and SARD) with buffer overflow vulnerabilities
- Derived program slices from code samples (for set of potentially vulnerable functions, eg. strcpy)
- Trained GLICE model
- Experimental results
  - comparison against original FUNDED model
  - evaluate trade-off call-tree depth vs. detection performance vs. resource usage

	FUNDED Original	FUNDED Improved	GLICE
Precision	0.7857	0.8133	0.9991
Recall	0.9961	0.9928	0.9980
F1-score	0.8784	0.8941	0.9986
Accuracy	0.8621	0.8824	0.9986

- Detection accuracy of GLICE improves up to 13% when compared to FUNDED, while training time for GLICE model is about 9 times smaller (target depth 4)

Target depth	0	1	2	3	4
Precision	0.8128	0.9508	0.9664	0.9822	0.9991
Recall	0.9943	0.9922	0.9930	0.9937	0.9980
F1-score	0.8944	0.9709	0.9795	0.9879	0.9986
Accuracy	0.8826	0.9703	0.9792	0.9878	0.9986

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Thanks!

Any questions?

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