A formal study of injection vulnerabilities and some tools it will enable

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Opening example

Question time

Complete the following sentence:

Paris is to ___ what London is to ___.

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Paris is to ___ what London is to ___.

First kind of answer

- France and England
- Leads to: "Paris is to France what London is to England."
- Proposed by those who understand the intent behind the question

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Opening example

Question time

Complete the following sentence:

Paris is to ___ what London is to ___.

First kind of answer

- France and England
- Leads to: "Paris is to France what London is to England."
- Proposed by those who understand the intent behind the question

Second kind of answer

- o crowded for you and that's and me
- Leads to: "Paris is too crowded for you and that's what London is to me."
- Proposed by those who know about injection attacks

What is an injection attack

Injection attack

An injection attack leverages a user input to modify the semantics of a sentence

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"The Voyage of Doctor Dolittle is canceled"

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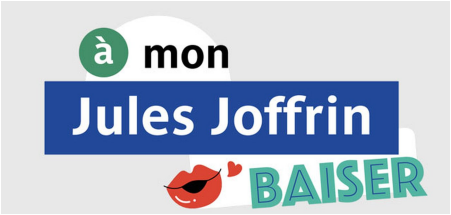

"À mon Jules Joffrin baiser"
"Jules Joffrin" is a Parisian subway station. The whole sentence means "I give a kiss to my boyfriend"

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And in software engineering?

SQL injection are well-known

A developer writes an authentication query:

```
SELECT id FROM user WHERE login='__' AND password='__'
```

If the user input is `admin` and `' OR 1=1--` it leads to:

```
SELECT id FROM user WHERE login='admin' AND password='' OR 1=1--'
```

Access granted!

And in software engineering?

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```

Access granted!

Injection-based attacks concern not only SQL...

- OS commands: Windows command line, bash
- Interpreted languages: JavaScript, python
- Formats: JSON, XML
- Protocols: SMTP, LDAP
- Markup languages: HTML, CSS

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What systems can be vulnerable?

Many systems process received instructions

- A browser receives and displays a page and executes scripts
- A database receives a query and applies it on its data
- A robot executes an order received though a network protocol

Injection vulnerabities

- These instructions may be *structured* using a query language, a protocol, etc.
- When instructions depend on user input, they are generally built by concatenation: it can lead to injection vulnerabilities
- Injections are very serious threats :
  - #1 threat to web services according to OWASP
  - Appears 3 times in CWE Top 25 Most Dangerous Software Errors

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What is this presentation about?

A formal approach

- Use the theory of formal language
- Formally define what is an injection attack
- Propose two security properties and analyze their decidability
- Highlight some vulnerable language patterns

A few tools derived from the formal approach

- A secure query language, a fuzzer and an intrusion detection system
- The objective of a provisional ANR project proposal

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1. Introduction
2. Background on formal language theory
3. Formalization and security properties
4. Results and implications
5. Ongoing and future projects

Formal language and grammar

The theory of formal languages studies the syntactic aspects of languages

Formal language

A formal language L is a set of valid strings called "words". Such string can be a SQL query, a C program, a network packet, etc.

Formal grammar

A grammar G describes a language $L(G)$ through a set of rewriting rules. If one can rewrite a starting symbol into a word by applying rules, then this word is in the language described by that grammar.

Each formal grammar describes one language, but each language can be described by several grammars: $L(G) = L(G') \not\Rightarrow G = G'$

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Grammar and derivation

Starting symbol: <Query>

<Query> → **SELECT** <SelList> **FROM** <FromList> **WHERE** <Condition>

<SelList> → <Attribute> | <Attribute> **,** <SelList>

<FromList> → <Table> | <Table> **,** <FromList>

<Condition> → <Condition> **AND** <Condition> | <Attribute> **IN (** <Query> **)**
| <Attribute> **=** <Attribute>

Grammar and derivation

Starting symbol: <Query>

<Query> → **SELECT** <SelList> **FROM** <FromList> **WHERE** <Condition>

<SelList> → <Attribute> | <Attribute> **,** <SelList>

<FromList> → <Table> | <Table> **,** <FromList>

<Condition> → <Condition> **AND** <Condition> | <Attribute> **IN (** <Query> **)**
| <Attribute> **=** <Attribute>

Derivation example

<*Query*> ⇒ **SELECT** <*SelList*> **FROM** <FromList> **WHERE** <Condition>

⇒ **SELECT** <Attribute> **FROM** <*FromList*> **WHERE** <Condition>

⇒ **SELECT** <Attribute> **FROM** <Table> **WHERE** <*Condition*>

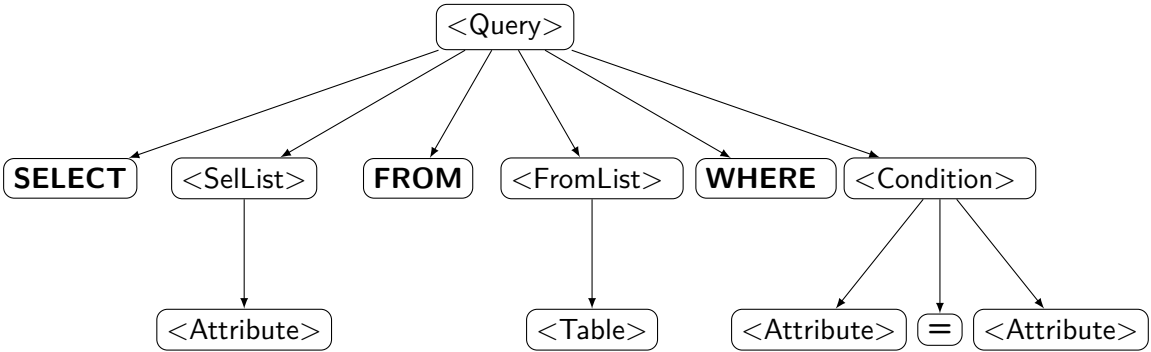
⇒ **SELECT** <Attribute> **FROM** <Table> **WHERE** <Attribute> **=** <Attribute>

We can also write directly:

<Query> ⇒* **SELECT** <Attribute> **FROM** <Table> **WHERE** <Attribute> **=** <Attribute>

Derivation tree

Derivation trees (= parse tree, concrete syntax tree) are another way of representing the set of rules used to derive a word



Grammar and language classes

Language classes

We can regroup languages into classes depending on their properties. Simpler languages are easier to parse but have less expressive power.

Grammar classes

For each language class, there is generally a grammar class with some restrictions about the form of the rules so these grammars generate that language class.

Informal presentation of some classical classes

- Regular language: all the languages that can be expressed with regular expression or finite-state automata
- Deterministic context-free language: languages that can be parsed in linear time
- Context-free language: languages whose words have parse trees

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Definitions

Query

A query is a complete command. For example: SQL query, JSON file, a network message, etc.

Template

A fill-in-the-blanks template **t** is the set of strings written by the developer. Example: `"SELECT __ FROM DB WHERE PRICE>__ AND ID=22"`

Injection

A user input **w** is the set of strings that is injected in a template. Example: `"NUMBER"` and `"23.99"`. Injection may be legitimate or malicious. In red

For simplicity sake, examples in this talk will be restricted to template with a single blank

How to modelize a malicious injection?

Intent

- We assume that the developer has an intent in mind when they writes the template.
- We modelize the intent with *a symbol or a sequence of symbol* denoted ι (for example: <Condition> or <Comparator> <Number>)
- **An injection w is legitimate if $\iota \Rightarrow^* w$**
- Languages and grammars don't deal with semantics... but compilers/interpreters do and rely on parsers, and parsers are based on grammars.
- It depends on the grammar and not only on the language!

Example

- Template: **SELECT** <Attribute> **FROM** <Table> **WHERE** <Attribute> **=** ␣
- Intent: <Attribute>
- Malicious injection: <Attribute> **AND** <Attribute>**=**<Attribute>

Intent-equivalence

Question

In which condition a template (p, s) can only accept legitimate injections?

Definitions

- First, we define the set of possible injections in this template :
  $F(L, (p, s)) = \{w \mid pws \text{ is a word of } L\}$
- Then, we define the set of injections that are expected by the developer :
  $E(G, \iota) = \{w \mid \iota \Rightarrow^* w\}$

Intent-equivalence

A template (p, s) is said to be *intent-equivalent* to ι if

$$S \Rightarrow^* p\iota s \qquad \text{and} \qquad F(L(G), (p, s)) = E(G, \iota)$$

i.e. if the intent is possible in that place and if the possible injections are exactly the expected

Intent-security

Question

In which condition a grammar can only generate intent-equivalent templates?

Definitions

- Let us define the set of injection of a whole grammar for a particular intent : $I(G,\iota) = \bigcup_{\{(p,s)|S \Rightarrow^* p\iota s\}} F(L(G),(p,s))$
- The set of *unexpected injections* is the set of injections that may appear in a template and that is not explained by the intent : $\delta I(G,\iota) = I(G,\iota) - E(G,\iota)$

Intent-security

A grammar is intent-secure for the intent ι if $\delta I(G,\iota) = \varnothing$.

Example

There is a grammar G such as $L(G) = \{a^n cdb^n \mid n \geq 0\}$ that is intent-secure for all symbols

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Inherently intent-(un)secure languages

The definitions of intent-equivalence and intent-security depend on a grammar

Inherently intent-secure languages

- A language whose grammars are all intent-secure
- They don't exist: we can always craft an insecure grammar

Inherently intent-insecure languages

- A language whose no grammar is intent-secure
- **SELECT * FROM product WHERE price =** ␣
  Here, the intent can be a number. We can inject `123 OR availability="true"`. Since this injection works for all grammars, SQL is inherently intent-insecure.

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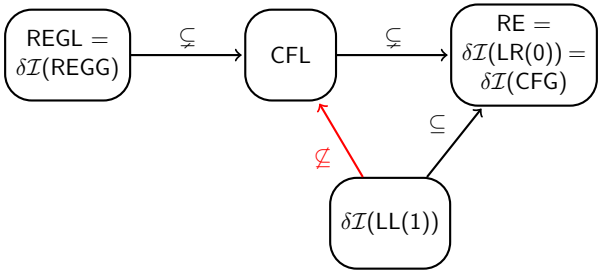
Intent-equivalence

- Intent-equivalence is decidable for regular and some deterministic grammars
- It is decidable for context-free grammars for terminal (non-derivable) intents, but undecidable with any intent.

	≥ 1 blanks $\iota \in (\Delta)^m$	≥ 1 blanks $\iota \in (\Delta^+)^m$	≥ 1 blanks $\iota \in (T^+)^m$
REGG	Decidable	Decidable	Decidable
VPG	Decidable	Decidable	Decidable
LR(0)	Decidable	Decidable	Decidable
LR(k)	Decidable	?	Decidable
CFG	Undecidable	Undecidable	Decidable

Injection characterization

- A language is regular iff it is the set of unexpected injections in a regular grammar
- Even simple grammars (LL(1)) can have complex (context-sensitive) injections
- A language can be described by a grammar iff it is the set of unexpected injections in a deterministic grammar



Intent-security

- All infinite regular languages (and languages that include infinite regular sublanguages) are inherently intent-insecure
- For two blanks, all context-free languages are inherently intent-insecure
- It is undecidable for one blank for deterministic grammars

	One blank	≥ 2 blanks
Finite, $\lvert L\rvert \geq 2$	Decidable	Decidable
REGG with infinite language	False	False
Grammars with infinite regular sublanguage	False	False
LR(0) with infinite language	Undecidable	False
CFG with infinite language	Undecidable	False

Intent-security

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Focus on infinite regular languages

All infinite regular languages (and languages that include infinite regular sublanguages) are inherently intent-insecure

Idea behind the impossibility

- The formal proof is based on the pumping lemma, but can be explained in a different way.
- The only way to have an infinite regular expression is to have a repetition with *. For example, in SQL: **SELECT** (<Attribute> **,**)* <Attribute> **FROM** <Table> is an infinite regular expression.
- In the template **SELECT** ⎵ **FROM** <Table>, one can inject **<Attribute>, <Attribute>** even if the intent is <Attribute>

Implication

It explains why so many languages are inherently intent-insecure: infinite regular patterns are ubiquitous! Another example: (**Condition OR**)* **Condition**

Focus on infinite context-free languages

For two blanks, all context-free languages are inherently intent-insecure

Idea behind the impossibility

- In infinite context-free languages, there exists $A \Rightarrow^* w_1 b A c w_2$ (w_1 and w_2 may be empty)
- A can be reached from the starting symbol S:
  $S \Rightarrow^* pAs \Rightarrow^* pw_1 bAcw_2 s \Rightarrow^* pw_1 bw_1 bAcw_2 cw_2 s$.
- Let the template be: $pw_1 \_\_ A \_\_ w_2 s$. The intents are b and c.
- We can inject $bw_1 b$ and $cw_2 c$ and get a valid word: $pw_1 bw_1 bAcw_2 cw_2 s$. It is an unexpected (malicious) injection
- Intuitively: with a recursive structure, one can add a level to the derivation tree by modifying both sides of the recursive structure

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Focus on infinite context-free languages (cont.)

Example

- Template: **SELECT** <Attribute> **FROM** <Table> **WHERE** ⎵ **IN (SELECT** <Attribute> **FROM** <Table> **) AND** <Attribute> **=** ⎵
- Intents: two <Attribute>
- Malicious injection:
  - <Attribute> **IN (SELECT** <Attribute> **FROM** <Table> **WHERE** <Attribute>
  - <Attribute> **)**
- Completed sentence: **SELECT** <Attribute> **FROM** <Table> **WHERE** <Attribute> **IN (SELECT** <Attribute> **FROM** <Table> **WHERE** <Attribute> **IN (SELECT** <Attribute> **FROM** <Table> **) AND** <Attribute> **=** <Attribute> **)**

Implication

This pattern is ubiquitous as well: any kind of recursive structure with tags, parenthesis, etc. This vulnerability needs blanks on both sides of the recursive structure.

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Implications

- The problem does not stem from bad development practice but from the languages themselves
- Template analysis (intent-equivalence) is possible for deterministic grammars but not for more complex grammars, but may require asking or guessing the developer's intent

Implications on language design

- It is possible (but not easy) to have intent-secure grammars
- Simpler languages are *not* more secure. On the contrary!
- Regular patterns with * should be avoided if they may contain a user input
- One should be vigilant with recursive structure if blanks can appear on both sides
- More complex, context-sensitive languages could be safe with two blanks or more
- Finite language are probably the most secure

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How to design an intent-secure language

Problem

- Intent-security is either false or undecidable for most grammar classes
- Could we find sufficient conditions for a grammar to be intent-secure?
- What would such language look like?

Sufficient conditions and necessary conditions

We found various sufficient conditions and necessary conditions. For example:

- An intent-secure grammar cannot have rules in the form $A \to \alpha B \beta$ and $A \to \alpha \delta \beta$ (because B could be replaced with δ)
- A grammar that is LL(1), RR(1), whose each expected injections set is prefix-free and suffix-free, and with no rule $A \to B$, is intent-secure for one blank and an intent of length 1.

How to design an intent-secure language

Proof of concept with SQL

We developed a proof of concept named SeQreL (secure-L) that is intent-secure for one blank and an intent of length 1. Compare for example:

- SQL: `SELECT ___ AS Orders, Min(Price) FROM Customers`
- SeQreL: `SELECT < AS[Orders,___], [MIN[(Price)]]> FROM Customers`

Ongoing work

- This language is context-free so it is not intent-secure with two blanks → we need to extend our definitions to context-sensitive languages
- In real-world applications, no need to have intent-security for all symbols
- We are looking for an actual case study: if you need to develop a DSL (domain-specific language) that would benefit of being intent-secure, contact me!

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A black-box injection fuzzer

Fuzzers

- A fuzzer is a testing tool that sends user input to a system to find its vulnerabilities
- Only a few injection-focused fuzzers, like sqlmap

Idea

- When the grammar and the template is known, it is easy to compute the set of injections
- In a black-box setting, the template could be inferred from the system answer

Poirot

- A universal black-box injection fuzzer that analyzes which injections are syntactically correct to infer the template (with any grammar)
- Based on an A* search, guided by an heuristic $\rightarrow$ theoretical guarantees
- Experiments with SQL, LDAP, XML, Bash and SMTP $\rightarrow$ still some performance issues

Intrusion detection and prevention system

Injection IDS

- Injection IDS exist but are rarely used because of their complexity
- They require source code or library modification, developer input, etc.
- We work on an IDS with minimal configuration and interaction: "plug and play"
- In particular: we don't assume access to the source code and we don't taint the template

Idea

- The IDS is a proxy placed between the back-end server and the database
- The difficulty is to identify the injection inside the query
- In development environment, the templates and their intents are inferred from queries
- In production environment, the query are verified with the learned templates. We can raise an alert or cancel the query if needed

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Provisional ANR project proposal

Objective: offer a methodological and technical toolbox to prevent, identify and mitigate injection threat in vulnerable systems

Main focuses

- Broaden the range of injection logic (insertion, overwrite, mixed)
- Take advantage of more elaborate theoretical constraints on interpreted languages (context-sensitive languages)
- Investigate possibility to take advantage of interpreter operational semantics to assess threats and mitigate them
- Investigate chained injection problems (controllability of the final interpreter)

Current team

- Pierre-François Gimenez, CentraleSupelec
- Eric Alata, LAAS-CNRS
- Benoît Morgan, IRIT
- Thomas Robert, Télécom Paris

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Conclusion

- Injection vulnerabilities are not specific to SQL but are present is all kind of languages and systems that handle user input within structured data
- Injection vulnerabilities do not stem from poor programming skills but from deep flaws in ubiquitous patterns, such as infinite regular expression and recursive bracket-based expression
- New tools are possible to detect, remove or limit these vulnerabilities
- **Contact us! We are looking for industrial partnerships and research collaborations.** pierre-francois.gimenez@centralesupelec.fr

And thank you for your attention!