Static Analysis

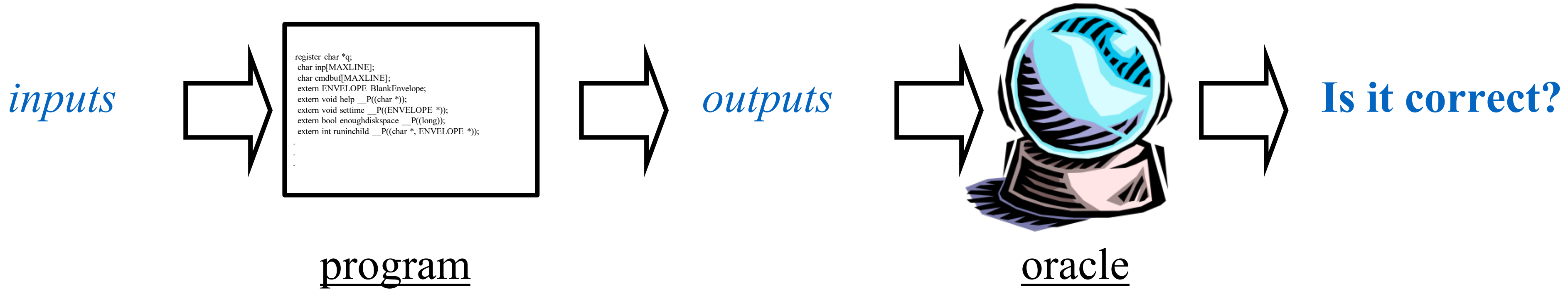
With material from Dave Levin, Mike Hicks, Dawson Engler, Lujo Bauer, Michelle Mazurek

http://philosophyofscienceportal.blogspot.com/2013/04/van-de-graaff-generator-redux.html

Static analysis

Current Practice

for Software Assurance



inputs

```
register char *q;
 char inp[MAXLINE];
 char cmdbuf[MAXLINE];
 extern ENVELOPE BlankEnvelope;
 extern void help __P((char *));
 extern void settime __P((ENVELOPE *));
 extern bool enoughdiskspace __P((long));
 extern int runinchild __P((char *, ENVELOPE *));
.
.
.
```

program

outputs

oracle

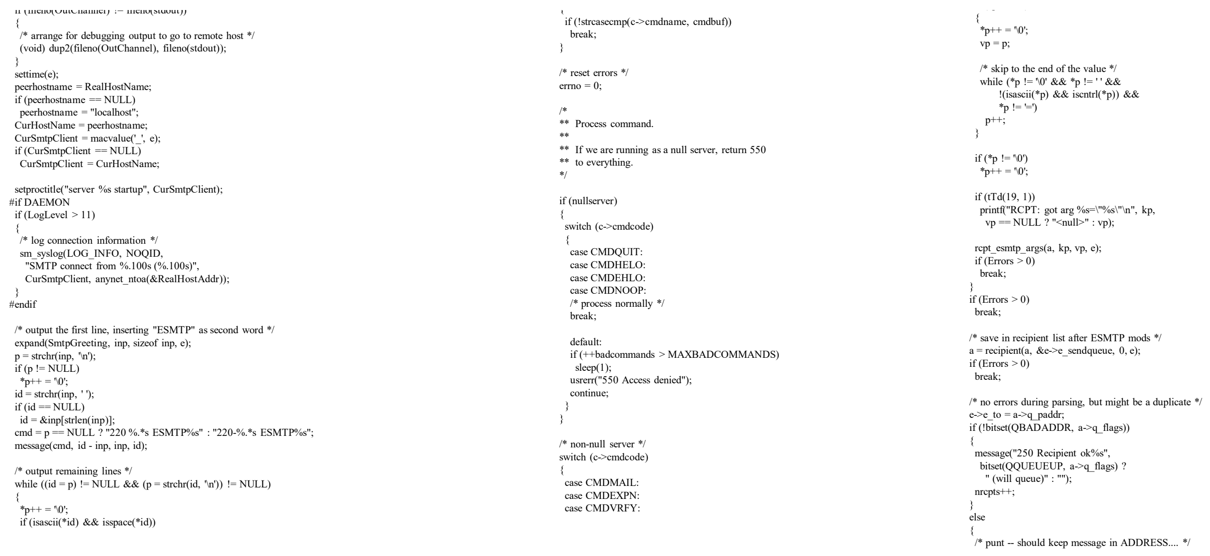
Is it correct?

- **Testing:** Check correctness on set of inputs
- **Benefits**: Concrete failure proves issue, aids fix
- **Drawbacks**: Expensive, difficult, coverage?
    - No guarantees

Current Practice

(continued)

- **Code audit:** Convince someone your code is correct
- **Benefit:** Humans can generalize
- **Drawbacks**: Expensive, hard, no guarantees



```
  if (fileno(OutChannel) != fileno(stdout))
  {
   /* arrange for debugging output to go to remote host */
   (void) dup2(fileno(OutChannel), fileno(stdout));
  }
  settime(e);
  peerhostname = RealHostName;
  if (peerhostname == NULL)
   peerhostname = "localhost";
  CurHostName = peerhostname;
  CurSmtpClient = macvalue('_', e);
  if (CurSmtpClient == NULL)
   CurSmtpClient = CurHostName;

  setproctitle("server %s startup", CurSmtpClient);
#if DAEMON
  if (LogLevel > 11)
  {
   /* log connection information */
   sm_syslog(LOG_INFO, NOQID,
    "SMTP connect from %.100s (%.100s)",
    CurSmtpClient, anynet_ntoa(&RealHostAddr));
  }
#endif

  /* output the first line, inserting "ESMTP" as second word */
  expand(SmtpGreeting, inp, sizeof inp, e);
  p = strchr(inp, '\n');
  if (p != NULL)
   *p++ = '\0';
  id = strchr(inp, ' ');
  if (id == NULL)
   id = &inp[strlen(inp)];
  cmd = p == NULL ? "220 %.*s ESMTP%s" : "220-%.*s ESMTP%s";
  message(cmd, id - inp, inp, id);

  /* output remaining lines */
  while ((id = p) != NULL && (p = strchr(id, '\n')) != NULL)
  {
   *p++ = '\0';
   if (isascii(*id) && isspace(*id))
```

```
 if (!strcasecmp(c->cmdname, cmdbuf))
  break;
}

/* reset errors */
errno = 0;

/*
**  Process command.
**
**  If we are running as a null server, return 550
**  to everything.
*/

if (nullserver)
{
 switch (c->cmdcode)
 {
  case CMDQUIT:
  case CMDHELO:
  case CMDEHLO:
  case CMDNOOP:
  /* process normally */
  break;

  default:
  if (++badcommands > MAXBADCOMMANDS)
   sleep(1);
  usrerr("550 Access denied");
  continue;
 }
}

/* non-null server */
switch (c->cmdcode)
{
 case CMDMAIL:
 case CMDEXPN:
 case CMDVRFY:
```

```
  {
   *p++ = '\0';
   vp = p;

   /* skip to the end of the value */
   while (*p != '\0' && *p != ' ' &&
       !(isascii(*p) && iscntrl(*p)) &&
       *p != '=')
    p++;
  }

  if (*p != '\0')
   *p++ = '\0';

  if (tTd(19, 1))
   printf("RCPT: got arg %s=\"%s\"\n", kp,
    vp == NULL ? "<null>" : vp);

  rcpt_esmtp_args(a, kp, vp, e);
  if (Errors > 0)
   break;
 }
 if (Errors > 0)
  break;

 /* save in recipient list after ESMTP mods */
 a = recipient(a, &e->e_sendqueue, 0, e);
 if (Errors > 0)
  break;

 /* no errors during parsing, but might be a duplicate */
 e->e_to = a->q_paddr;
 if (!bitset(QBADADDR, a->q_flags))
 {
  message("250 Recipient ok%s",
   bitset(QQUEUEUP, a->q_flags) ?
    " (will queue)" : "");
  nrcpts++;
 }
 else
 {
  /* punt -- should keep message in ADDRESS.... */
```

- How can we do better?

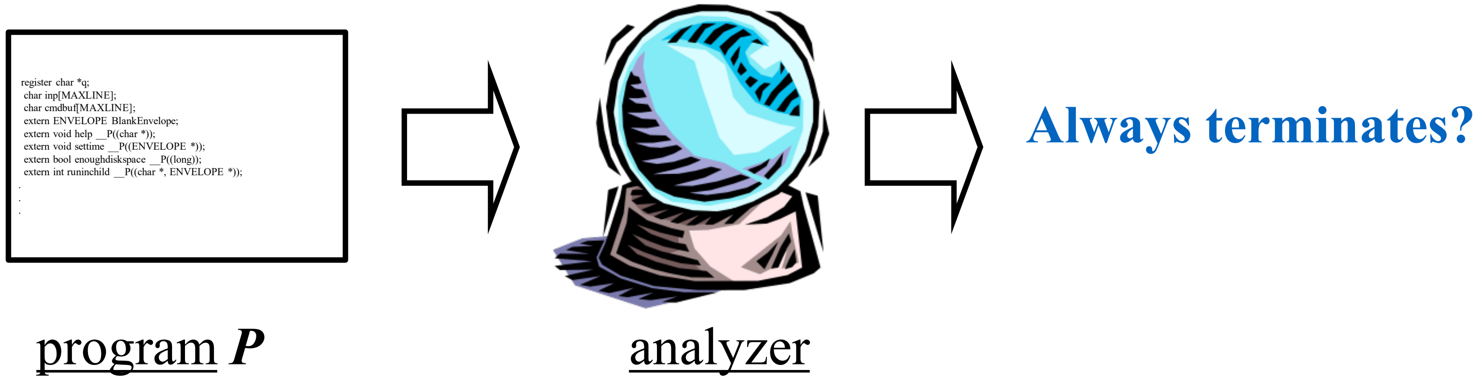
Static analysis

- Analyze program’s code without running it
  - In a sense, ask a computer to do code review

- **Benefit:** (much) **higher coverage**
  - Reason about many possible runs of the program
    - Sometimes *all of them*, providing a **guarantee**
  - Reason about incomplete programs (e.g., libraries)

- **Drawbacks:**
  - Can only analyze limited properties
  - May miss some errors, or have false alarms
  - Can be time- and resource-consuming

The Halting Problem



```
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.
.
.
```

- Can we write an analyzer that can prove, for any program *P* and inputs to it, *P* will terminate?
  - Doing so is called the **halting problem**
  - Unfortunately, this is **undecidable:** any analyzer will fail to produce an answer for at least some programs and/or inputs

Some material inspired by work of Matt Might: http://matt.might.net/articles/intro-static-analysis/

Check other properties instead?

- Perhaps security-related properties are feasible
  - E.g., that all accesses `a[i]` are in bounds
  - That a certain line of code is reachable

- *But* these **properties can be converted into the halting problem** by transforming the program
  - A perfect array bounds checker could solve the halting problem, which is impossible!

- Other undecidable properties (Rice's theorem)
  - Does this **SQL string** come from a **tainted source**?
  - Is this **pointer used after** its memory is **freed**?
  - Do any variables experience **data races**?

So is static analysis impossible?

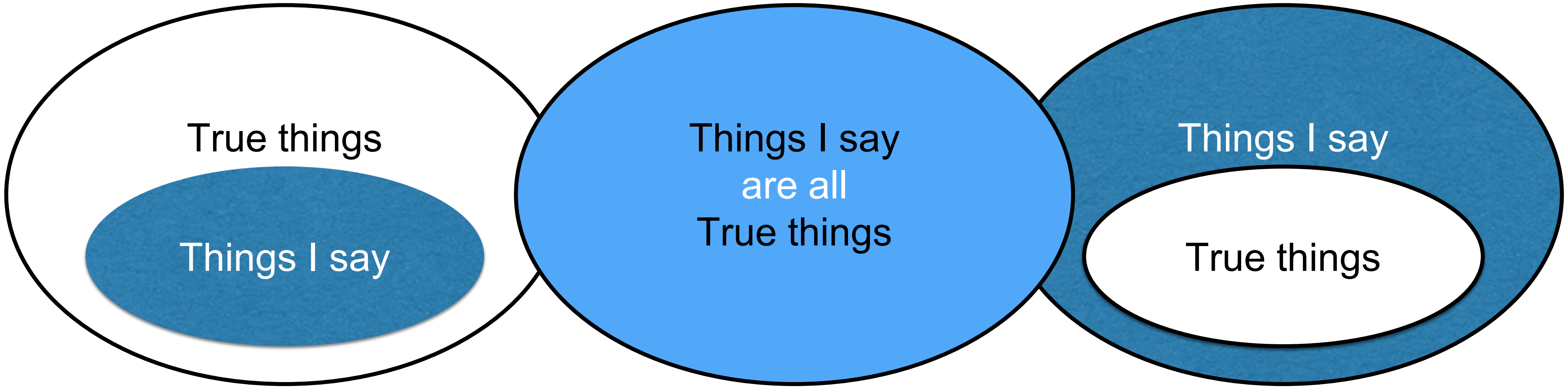
- **Perfect** static analysis is **not possible**
- **Useful** static analysis is **perfectly possible**, despite
  1. **Nontermination** - analyzer never terminates, or
  2. **False alarms** - claimed errors are not really errors, or
  3. **Missed errors** - no error reports ≠ error free
- Nonterminating analyses are confusing, so tools tend to exhibit only false alarms and/or missed errors

Completeness

If analysis says that X is true, then X is true.

Soundness

If X is true, then analysis says X is true.



Trivially Complete: Say nothing

Trivially Sound: Say everything

Sound and **Complete**:
Say exactly the set of true things

Stepping back

- **Soundness**: No error found = no error exists
  - Alarms may be false errors
- **Completeness**: Any error found = real error
  - Silence does not guarantee no errors
- Basically any useful analysis
  - is neither **sound** nor **complete** (def. not **both**)
  - … usually *leans* one way or the other

Adding some depth: Taint (flow) analysis

Tainted Flow Analysis

- Cause of many attacks is **trusting unvalidated input**
  - Input from the user (network, file) is **tainted**
  - Various data is used, assuming it is **untainted**
- Examples expecting untainted data
  - source string of `strcpy` (≤ target buffer size)
  - format string of `printf` (contains no format specifiers)
  - form field used in constructed SQL query (contains no SQL commands)

Recall: Format String Attack

- Adversary-controlled format string

```
char *name = fgets(.., network_fd);
printf(name);      // Oops
```

- Attacker sets name = `"%s%s%s` “ to crash program
- Attacker sets name = `"%n"` to write to memory
  - Yields code injection exploits

- These bugs still occur in the wild occasionally
  - Too restrictive to forbid non-constant format strings

The problem, in types

- Specify our requirement as a *type qualifier*

```
int printf(untainted char *fmt, ..);
tainted char *fgets(..);
```

- **tainted** = possibly controlled by adversary
- **untainted** = must not be controlled by adversary

```
tainted char *name = fgets(..,network_fd);
printf(name);    // FAIL: tainted ≠ untainted
```

Analyzing taint flows

- **Goal**: For all possible inputs, prove tainted data will never be used where untainted data is expected
  - **untainted** annotation: indicates a **trusted sink**
  - **tainted** annotation: an **untrusted source**
  - *no annotation* means: not sure (analysis must figure it out)

- Solution requires inferring **flows** in the program
  - What **sources can reach what sinks**
  - If any flows are *illegal*, i.e., whether a **tainted** source may flow to an **untainted** sink

- We will aim to develop a *sound* analysis

Legal Flow

```
void f(tainted int);
untainted int a = ..;
f(a);
```

f accepts **tainted** *or* **untainted** data

untainted ≤ **tainted**

Illegal Flow

```
void g(untainted int);
tainted int b = ..;
g(b);
```

g accepts *only* **untainted** data

tainted ≰ **untainted**

Define allowed flow as a **lattice:**

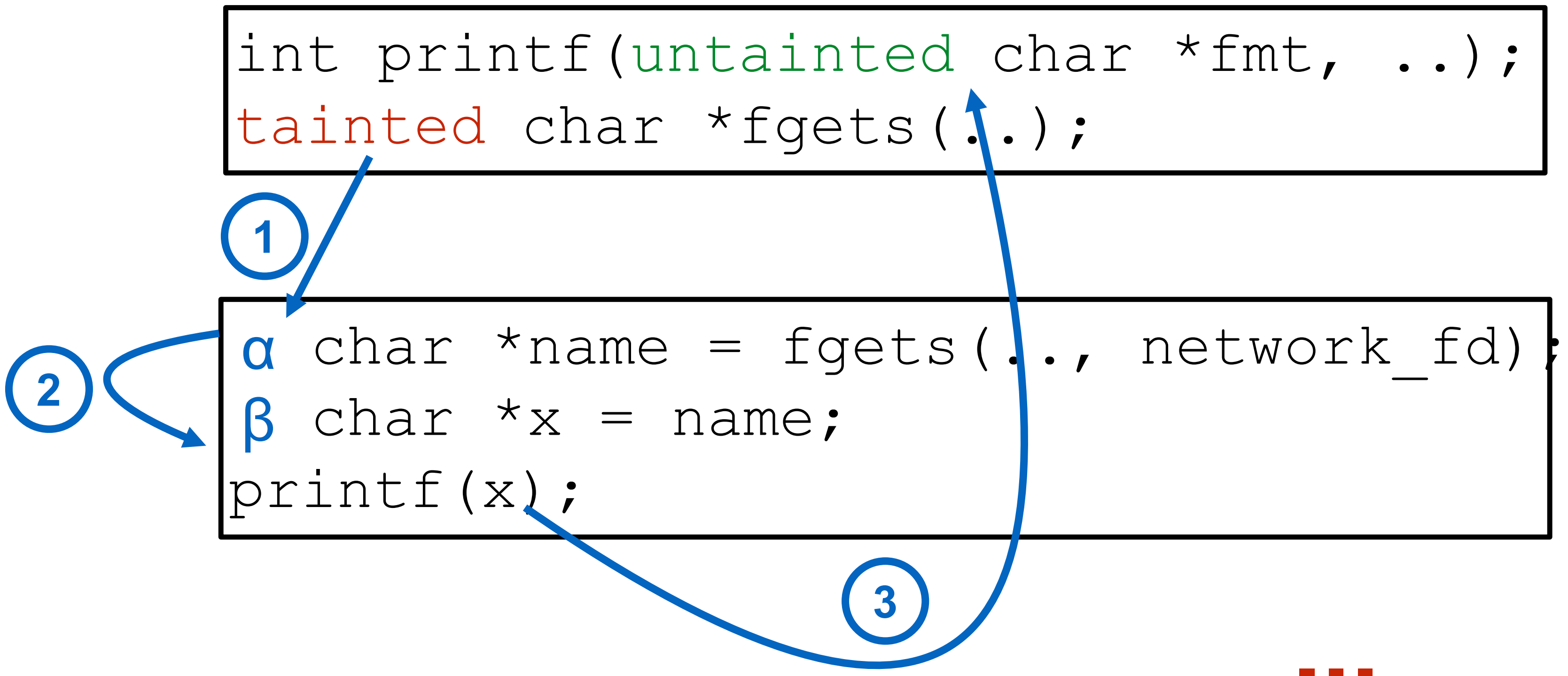
untainted < **tainted**

At each program step, **test** whether inputs ≤ policy

Analysis Approach

- If no qualifier is present, we must **infer** it
- Steps:
  - **Create** a **name** for each missing qualifier (e.g., α, β)
  - For each program statement, **generate constraints**
    - Statement `x = y` generates constraint $q_y \leq q_x$
  - **Solve the constraints** to produce solutions for α, β, etc.
    - A solution is a *substitution* of qualifiers (like **tainted** or **untainted**) for names (like α and β) such that all of the constraints are legal flows
- If there is **no solution**, we (may) have an **illegal flow**

Example Analysis



```
int printf(untainted char *fmt, ..);
tainted char *fgets(..);
```

```
α char *name = fgets(.., network_fd);
β char *x = name;
printf(x);
```

① **tainted** ≤ α

② α ≤ β

③ β ≤ **untainted**

Illegal flow!

No possible solution for α and β

First constraint requires α = **tainted**
To satisfy the second constraint implies β = **tainted**
But then the third constraint is illegal: **tainted ≤ untainted**

Taint Analysis: Adding ***Sensitivity***

But what about?

```
int printf(untainted char *fmt, ..);
tainted char *fgets(..);
```

```
→ α char *name = fgets(.., network_fd);
  β char *x;
  x = name;
  x = "hello!";
  printf(x);
```

$\textbf{tainted} \le \alpha$

$\alpha \le \beta$

$\textbf{untainted} \le \beta$

$\beta \le \textbf{untainted}$

No constraint solution. Bug?

False Alarm!

Flow Sensitivity

- Our analysis is **flow *in*sensitive**
  - Each variable has **one qualifier**
  - Conflates the taintedness of all values it ever contains
- **Flow-sensitive analysis** accounts for variables whose contents change
  - Allow each assigned use of a variable to have a different qualifier
    - E.g., α_1 is x's qualifier at line 1, but α_2 is the qualifier at line 2, where α_1 and α_2 can differ
  - Could implement this by transforming the program to assign to a variable at most once

Reworked Example

```
int printf(untainted char *fmt, ..);
tainted char *fgets(..);
```

```
→ α char *name = fgets(.., network_fd);
char β *x1, γ *x2;
x1 = name;
x2 = "hello!";
printf(x2);
```

tainted ≤ α

α ≤ β

untainted ≤ γ

γ ≤ **untainted**

No Alarm

Good solution exists:

γ = **untainted**

α = β = **tainted**

Handling conditionals

```
int printf(untainted char *fmt, ..);
tainted char *fgets(..);
```

```
→ α char *name = fgets(.., network_fd);
  β char *x;
  if (..)   x = name;
  else     x = "hello!";
  printf(x);
```

tainted ≤ α

α ≤ β

~~**untainted** ≤ β~~

β ≤ **untainted**

Constraints still unsolvable

Illegal flow

Multiple Conditionals

```
int printf(untainted char *fmt, ..);
tainted char *fgets(…);
```

```
  void f(int x) {
    α char *y;
→   if (x) y = "hello!";
    else   y = fgets(.., network_fd);
    if (x) printf(y);
  }
```

~~untainted ≤ α~~

tainted ≤ α

α ≤ untainted

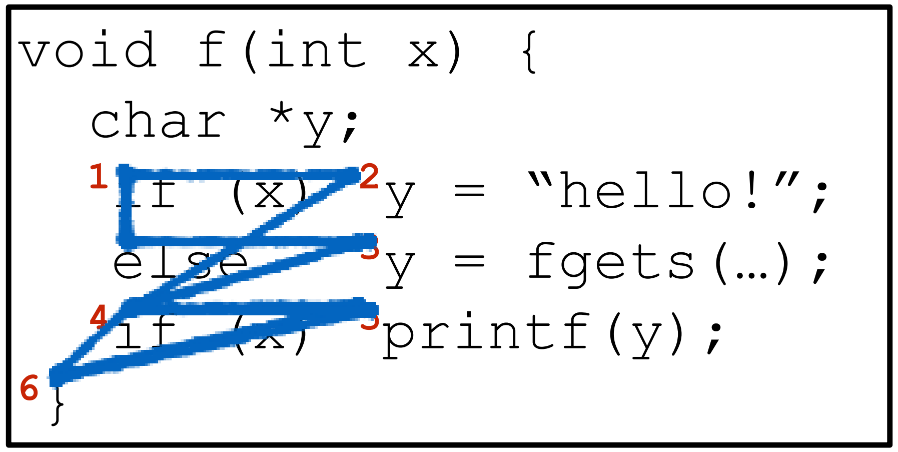
No solution for α. Bug?

False Alarm!

(and flow sensitivity won’t help)

Path Sensitivity

- Consider *path feasibility*. E.g., `f(x)` can execute path
  - **1-2-4-5-6** when $x \neq 0$, or
  - **1-3-4-6** when $x == 0$. But,
  - path **1-3-4-5-6** *infeasible*



```
void f(int x) {
  char *y;
  if (x) y = "hello!";
  else   y = fgets(…);
  if (x) printf(y);
}
```

- A **path sensitive analysis** checks feasibility, e.g., by qualifying each constraint with a **path condition**
  - $x \neq 0 \Rightarrow$ **untainted** $\leq \alpha$ (segment 1-2)
  - $x = 0 \Rightarrow$ **tainted** $\leq \alpha$ (segment 1-3)
  - $x \neq 0 \Rightarrow \alpha \leq$ **untainted** (segment 4-5)

Static analysis in practice

coverity®
A Synopsys Company

GRAMMATECH

hp Fortify

klocwork®
a Rogue Wave Company

VERACODE

FindBugs™

LLVM

clang analyzer
&
KLEE

Joern

Caveat: appearance in the above list is not an implicit endorsement, and these are only a sample of available offerings